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FULL-SCALE DESULFURIZATION OF STACK GAS BY DRY LIMESTONE INJECTION. VOLUME II. APPENDICES A THROUGH H

F. E. Gartrell

Tennessee Valley Authority

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Environmental Protection Agency

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The report gives results of a test program of dry limestone injection, demonstrated on a 150-Mw pulverized-coal-fired boiler at TVA's Shawnee Plant. The program included: equipment shakedown, dust distribution studies, process optimization, and long-term injection trials. It identified major process variables; evaluated distribution of lime dust in the boiler, effect of operating variables on distribution, and resulting effects on SO2 removal; evaluated the sensitivity of SO2 removal to key operating and process variables; evaluated conditions for optimum SO2 removal; studied process effects on boiler operation and maintenance, on solids collection equipment, and on water quality; and completed a process economics study. The program is discussed in context with previous investigations and EPA-sponsored support activities. Appendices contain test program detail results and results of EPA support projects. Because of low SO2 removal efficiencies and the potential for major reliability problems, it does not appear that dry limestone injection will play an important role in controlling SO2 emissions from power plants.

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Reliability
Electric Power Plants
Flue Gases

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Dry Limestone Injection

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VOLUME II -
APPENDICES A THROUGH H

by
Tennessee Valley Authority
Chattanooga, Tennessee

Interagency Agreement TV-30541A

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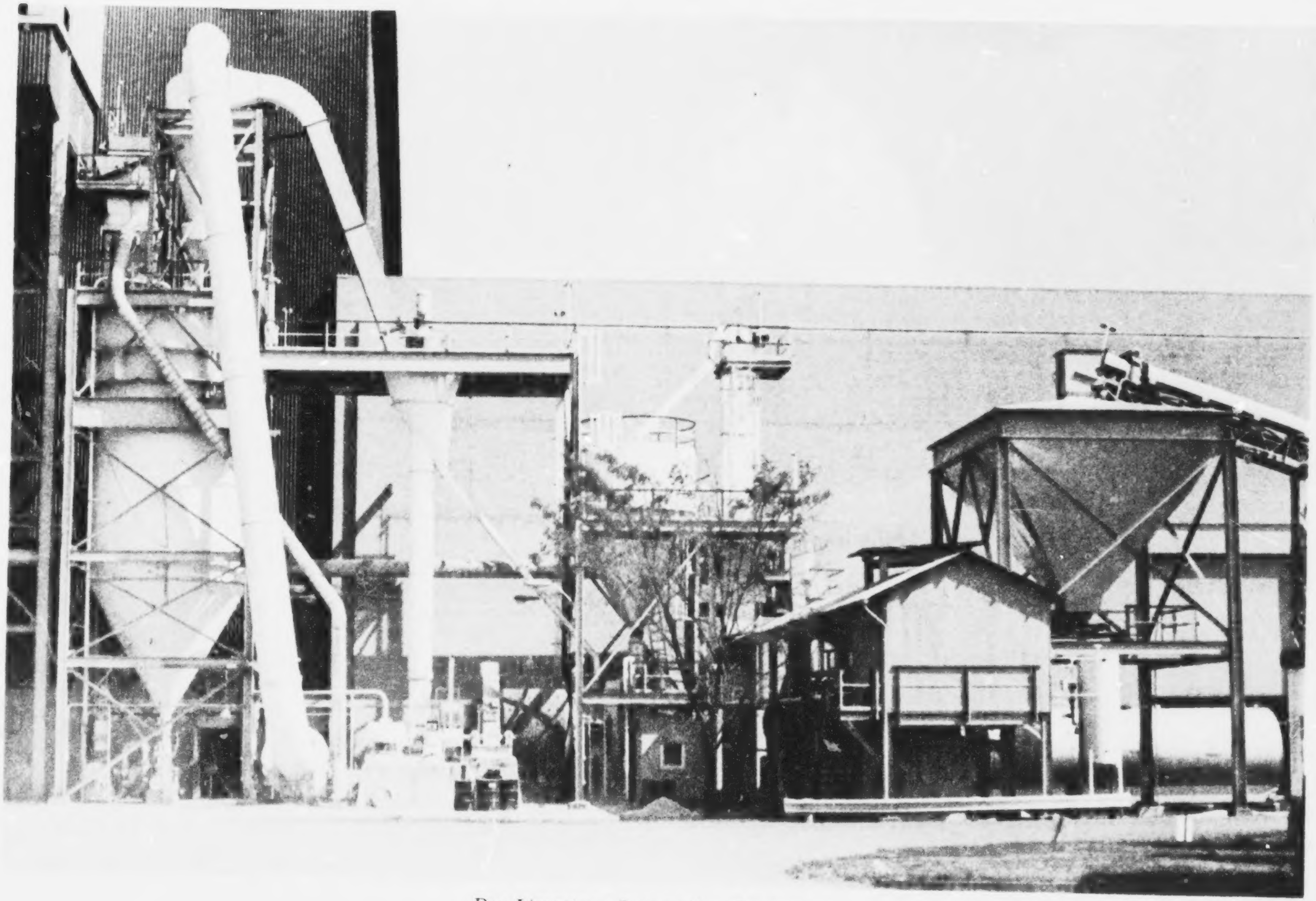

Dry Limestone Preparation Equipment

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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CONVERSION TABLE

EPA policy is to express all measurements in Agency documents in metric units. When implementing this policy results in undue cost or difficulty in clarity, the National Environmental Research Center-Research Triangle Park (NERC-RTP) provides conversion factors for the particular nonmetric units used in the document. For this report these factors are:

British		Metric
Multiply	By	To Obtain
feet	3.0480×10^{-1}	meters
feet^2	9.29×10^{-2}	meters^2
feet/sec.	3.0480×10^{-1}	feet/sec.
feet^3 /min.	4.720×10^{-1}	liters/sec.
grains (troy)	6.48×10^{-2}	grams
grains/dry s.c.f. @ 70° F	2.464	grams/meter^3 @ 0° C
gallon	3.785	liters
inch	2.5400×10^{-2}	meters
micron	1.0×10^{-6}	meters
ounce (troy)	3.1103×10^{1}	grams
pound	4.536×10^{-1}	kilograms
pound/in.^{2}	7.03×10^{-2}	kg/cm^2
quart	9.463×10^{-1}	liters
tons/hr.	2.520×10^{-1}	kg/sec.

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APPENDIX A

Statistics on Boiler and Limestone System

SHAWNEE STEAM PLANT STATISTICS

GENERAL DATA

Location

On left bank of Ohio River 13 miles downstream from mouth of Tennessee River at Paducah, Kentucky

Access

Highway	1.1 miles constructed from Kentucky State Highway No. 305
Railroad	3.4 miles constructed from Paducah & Illinois Railroad at Chiles, Kentucky
Water	Coal unloading dock on 9-ft navigable channel connected with Inland Waterway System

Chronology

Initial appropriations:	
Units 1-4	January 6, 1951
Units 5-6	July 5, 1952
Units 7-10	July 15, 1952
Construction started at site	January 6, 1951
Commercial operation:	
Unit 1	April 9, 1953
Unit 2	June 21, 1953
Unit 3	October 10, 1953
Unit 4	January 8, 1954
Unit 5	October 1, 1954
Unit 6	November 1, 1954
Unit 7	December 23, 1954
Unit 8	March 15, 1955
Unit 9	July 19, 1955
Unit 10	1956

Power Installation

Rated capacity, units 1-10	135,000 kw each; 1,350,000 kw total
Capability, units 1-10	150,000 kw each; 1,500,000 kw total

Coal Consumption (approx)

Annual, 10-unit plant	4,100,000 tons based on 80 percent plant load factor
Per hour, each unit	58 tons operating at rated load
Per kwh, each unit	0.78 lb based on 12,000 Btu per lb coal and operating at max. capability and 2 in. Hg absolute exhaust pressure

Throttle Operating Conditions

Pressure	1800 psig
Temperature	1000° F

Construction Quantities (estimated totals)

Excavation (incl hydraulic)	3,250,000 cu yd
Fill (incl hydraulic)	2,350,000 cu yd
Concrete	290,000 cu yd
Reinforcing steel	18,000 tons
Formwork	2,000,000 sq ft
Structural steel (main contracts):	
Powerhouse	25,980 tons
Service bay	960 tons
Switchyard and transformer yard	600 tons
Masonry	2,677,950 units
Galbestos siding (powerhouse)	155,600 [illegible] ft

Cost (estimated)

Generating plant	$207,477,000; $138 per kw of capability
Switchyard	$8,523,000
Total project	$216,000,000; $144 per kw of capability

Datum

Elevations are based on preliminary elevations established by the U. S. C. & G. S. in 1946 and 1947 and subject to correction when the leveling is adjusted to conform to the Standard Datum.

POWERHOUSE & SERVICE BAY

Structural Data

Foundation:	
Material	Water-bearing gravelly sand stratum; uplift controlled by relief well system
Allowable bearing pressures:	
Powerhouse	5 tons per sq ft
Service bay	2 tons per sq ft
Type of construction:	
Substructure	Reinforced concrete
Superstructure	Masonry and steel
Principal dimensions:	
Powerhouse	882- by 120-ft turbine room, 853- by 141-ft boiler room and heater bay; maximum height: 139 ft above basement floor, 99 ft above ground
Service bay (shops and office)	204 by 215 ft
Turbine room cranes	2; 90-ton capacity each; manufactured by Cyclops Iron Works
Stacks (1 per unit)	Reinforced concrete with brick lining; 14 ft id at top; 250 ft high above ground; built by Custodis Construction Co., Inc.

Architecture

Exterior walls	Steel frame, gray face brick base with insulated maroon asbestos-protected steel V-beam siding; glass block south wall turbogenerator room
Interior walls	Glazed tile and perforated acoustical steel panels in turbogenerator room; glazed tile in toilets and locker rooms, unglazed tile elsewhere; glazed tile and gray face brick in public areas; plaster and movable metal partitions in office areas; marble walls in public rest rooms
Roof	Smooth-surface asphalt and felt built-up roofing over rigid insulation on precast concrete slabs and cellular steel decking
Floors	"Greytone" quarry tile in turbogenerator room and boiler bay; terrazzo in toilets, public areas, and corridors; rubber tile in offices; colored metallic hardened cement elsewhere
Windows	Steel and aluminum projected type sash and special assemblies of aluminum frames and porcelain enameled panels in offices and entrances

Steam Generators

General Data

Manufacturer	Babcock & Wilcox Co.
Type	Radiant reheat
Rated capacity, each unit	1,000,000 lb steam per hr
Max. 4-hour capacity, each unit	1,100,000 lb steam per hr
Steam pressure (at superheater outlet)	1825 psig
Steam temperature (at superheater outlet)	1003° F
Efficiency (guaranteed at rated load)	88.33 percent

Drums (1 per unit)

Location	El. 417.0
Size	66 in. id, 62.5 ft long, 6-1/8-in. wall
Weight	321,000 lb
Design pressure	2050 psig

Furnaces

Type	Water cooled, divided by center wall with one hopper each side, manually adjustable air register
Principal dimensions	46 ft wide by 24 ft deep by 95 ft high
Heating surface	14,770 sq ft
Total volume	72,000 cu ft

Steam Generators--Continued

Superheaters (primary and secondary)

Type	Continuous tube, pendant
Tube size	2 in. od
Heating surface	68,500 sq ft
Design pressure	2050 psig
Design temperature	1003° F

Reheaters

Type	Continuous tube, pendant
Tube size	2 in. od
Rated capacity, each unit	870,000 lb per hr
Design pressure	510 psig
Design temperature	1003° F
Operating inlet pressure	425 psig, design*
Operating outlet pressure	403 psig, design*
Operating inlet temperature	640° F, design*
Operating outlet temperature	1003° F, design*

---

* Varies with load.

Air Preheaters (2 per unit)

Manufacturer	Air Preheater Corp.
Type	Ljungstrum, counterflow, regenerative
Size	25-vane, 54-in. elements, 66-in. casing
Heating surface	118,600 sq ft each
Design temperature gases:	
Entering	719° F
Leaving	306° F uncorrected
Design temperature air:	
Entering	80° F
Leaving	608° F

Firing Equipment (per unit)

Burners	16; forced draft, circular
Pulverizers	4; spring-loaded ball bearings
Feeders	4; integrally mounted
Lighting-off torches	16; oil-mechanical atomization-electric ignition

Controls

Combustion	Electronic-pneumatic; manufactured by Republic Flow Meters Co.
Feedwater	3-element, electronic-pneumatic, mfd by Republic Flow Meters Co.
Superheater and reheater	Desuperheater and gas recirculating; mfd by Bailey Meter Co.

Fans

Forced Draft (2 per unit)

Type and size	American H.S., single inlet; No. 900
Manufacturer	American Blower Corp.
Rated capacity	208,000 cfm each
Rated static pressure (at test block)	10.8 in. H_2O
Rated temperature (at test block)	140° F
Control	Inlet louvers
Design temperature (air leaving fan)	140° F
Motors	500 hp, 707 rpm, squirrel cage, drip-proof protected; mfd by Allis-Chalmers Mfg Co.

Induced Draft (2 per unit)

Type and size	Sirocco, double inlet; No. 775
Manufacturer	American Blower Corp.
Rated capacity	292,000 cfm each
Rated static pressure (at test block)	16 in. H_2O
Rated temperature (at test block)	320° F
Control	Inlet louvers
Motors	1000 hp, 586 rpm, squirrel cage, drip-proof protected; mfd by Allis-Chalmers Mfg Co.

Ash Handling

Method

Bottom ash	Jetted from two hoppers by high-pressure water through transport piping to disposal area
Dry fly ash	Exhausted by vacuum created by water jets in hydroveyor and jetted to disposal area

Fly Ash Collectors (2 per unit)

Type and size	AC-130 cyclone; 4 groups of 4 No. 13FAC
Manufacturer	Buell Engineering Co., Inc.
Rated capacity	239,000 cfm @ 305° F
Efficiency	85 percent (guaranteed overall)
Pressure drop	3.05 in. H_2O at rated capacity

Bottom Ash System

Type	Manually operated hydraulic jetting system to fill
Manufacturer	United Conveyor Corp.

Water Pumps

Bottom ash sluice	5 (total)--3, 8-in. discharge, 10-in. suction; SDO type; 2800-gpm rated capacity; 735-ft head; mfd by Byron-Jackson Co.; 2, 10-in. discharge, 10-in. suction; DMD type; 2800-gpm rated capacity; 710-ft head; mfd by Economy Pumps, Inc.
Fly ash sluice	4; TU type; 2300-gpm rated capacity; 480-ft head; mfd by Peerless Pump Division

Dust Collectors

At Coal Bunkers (1 per unit)

Type and capacity	Cyclone; 4500 cfm
Manufacturer	Kirk & Blum Mfg Co.

At Coal Scales (1 per unit)

Type and capacity	Multiclone; 1200 cfm
Manufacturer	Western Precipitation Corp.

At Coal Conveyor Transfer Point (2 - total)

Type and capacity	Multiclone; 4500 cfm
Manufacturer	American Blower Corp.

Turbogenerators

Foundations

Type	Reinforced concrete frame

Turbines

Manufacturer	Westinghouse Electric Corp.
Type and speed	Tandem compound, triple-flow exhaust, condensing, reheat; 3600 rpm
Rated capacity, each unit	135,000 kw
Maximum capability, each unit	150,000 kw
Throttle pressure	1800 psig
Throttle temperature	1000° F
Reheated steam pressure	300 psig at capability load
Reheated steam temperature	1000° F at capability load
Number of stages, each unit	44
Extraction points and stage numbers	7 (16, 21, 30, 36, 38, 40, 42)
Design backpressure	2 in. Hg absolute
Total rotor weight	105,000 lb
Turbine heat rate (guaranteed at maximum capability and 2 in. Hg absolute exhaust pressure)	7807 Btu per kwh
Net plant heat rate (expected at maximum capability and 2 in. Hg absolute exhaust pressure)	9398 Btu per kwh

Turbogenerators--Continued

Generators

Manufacturer	Westinghouse Electric Corp.
Rating, each	150,000 kva, 135,000 kw, 0.9 pf, 3 ph, 60 cy, 18,000 v, 3600 rpm, 4810 amp, 0.9 scr
Maximum capability, each	168,540 kva, 150,000 kw, 0.89 pf, 5400 amp
Temperature rise	Stator, 60° C; rotor, 85° C
Cooling	Hydrogen, 0.5 psig @ rated capacity, 15 psig @ maximum capability
Hydrogen treatment	Vacuum detraining
Rotor weight	105,000 lb
Stator weight	397,600 lb
Excitation:	
Units 1-6	Pilot exciter
Units 7-10	Magamp amplifier
Exciter rating	350 kw, 375 v, 900 rpm, shunt wound, direct connected
Pilot exciter rating:	
Units 1-6	3.0 kw, 250 v, 900 rpm, compound wound, direct connected
Units 7-10	13 kw, 125 v, 1745 rpm, magamp type, motor generator set
Neutral grounding	Transformer, 75 kva, 18,000-220 v; secondary resistor, 0.27 ohm, 470 amp (60 sec)
Surge protection	Lightning arresters only

Generator Leads

Connections	Unit type, no generator voltage switching
Rating (at 35° C rise above 40° C ambient temperature indoor)	6000 amp
Bus material:	
Units 1-4	Square copper tubing
Units 5-10	Two aluminum channels
Bus enclosure:	
Indoor	Segregated phase
Outdoor	Expanded aluminum and aluminum framing supported on structural steel
Manufacturer	Designed and fabricated by TVA

Auxiliary Power

Voltage

Normal, starting and emergency supply	4160 and 480 volts

Common and Unit Boards

Voltage and type	4160 and 480 v; metal-clad switchgear
Breaker rating:	
4160-volt	250,000 kva
480-volt	25,000 amp
Manufacturer:	
4160-volt	Westinghouse Electric Corp.
480-volt	I-T-E Circuit Breaker Co.

Control Batteries

Voltage and rating	250 volts; 1 hr, 474 amp
Type	25-plate, heavy-duty, glass-cell
Manufacturer	Electric Storage Battery Co.

Condensers (1 per unit)

General Data

Type	Horizontal, single pass, surface
Manufacturer	Foster Wheeler Corp.
Surface area	70,000 sq ft

Design Conditions (at rated load)

Steam condensed, each unit	695,000 lb per hr
Backpressure	2 in. Hg absolute
Cooling water:	
Flow	107,600 gpm
Temperature	79° F
Tube velocity	7.07 ft per sec
Tube cleanliness	85 percent

Condensers--Continued

Tubes

Number, each unit	10,300
Dimensions, each tube:	
Outside diameter	7/8 in.
Overall length	30 ft
Material	Inhibited admiralty
Manufacturer:	
Units 1-4	Wolverine Tube Division
Units 5-10	Revere Copper & Brass, Inc.

Feedwater Equipment

Closed Heaters (6 per unit)

Type	Horizontal
Manufacturer	The Lummus Co.
Shell design pressure:	
Heater No.	
1	650 psig
2	475 psig
3	250 psig
5, 6, 7	50 psig and 30 in. Hg vac
Tubes:	
Design pressure, psig	HP heaters, 2900; LP heaters, 250
Material	HP, 70-30 Cu Ni; LP, inhibited admiralty

Deaerating Heaters (1 per unit)

Type	Deaerating tray
Manufacturer	Cochrane Corp.
Storage tank dimensions	11 ft diam, 42 ft 4 in. overall length
Design pressure	65 psig
Capacity	1,038,340 lb per hr

Evaporators (1 per unit)

Type	Horizontal, single effect
Manufacturer	The Lummus Co.
Evaporative capacity	20,000 lb per hr
Design pressure	Shell, 75 psig; tube, 225 psig
Design temperature	Shell, 350° F; tube, 850° F
Tube material	Monel

Boiler Feedwater Pumps (3 per unit)

Stages and type	11-stage; horizontal, centrifugal
Rated capacity, each	1102 gpm
Rated head	6140 ft
Manufacturer	Ingersoll-Rand Co.
Motors	2000 hp, 3570 rpm, manufactured by Elliott Mfg Co.

Condensate Pumps (2 per unit)

Stages and type	3-stage vertical
Rated capacity, each	1700 gpm
Rated head	370 ft
Manufacturer	Foster Wheeler Corp.
Motors	250 hp, 1160 rpm, manufactured by General Electric Co.

Internal Water Treatment

Sodium phosphate pumps	10; duplex-plunger type; manufactured by Proportioneers, Inc.; 65.4 gph @ 2300 psi rated capacity; 5-hp motor
Sodium sulphite and sodium hydroxide pumps	12; duplex-plunger type, one head for sulphite and one for caustic; mfd by Proportioneers, Inc.; 2.27 gph @ 750 psi rated cap. each head; 1/3-hp motor

Mechanical Control Equipment

Unit Control Room

Principal features	Centralized control; two units in one room; supplied by Republic Flow Meters Co.

Principal Piping

Fabricator

Benjamin F. Shaw Co.

Main Steam

Material:	
Units 1-4	Alloy steel; A-182-49T; 2-1/4% Cr, 1% Mo
Units 5-10	Alloy steel; A-158-50T-P11; 1-1/4% Cr, 1/2% Mo
Design pressure	1935 psig
Design temperature	1003° F
Flow sections:	
Full	16.25 in. od, 2.375 in. wall thickness
Half	13.5 in. od, 2 in. wall thickness

Steam to Reheater

Material	Steel A-106, Grade B
Design pressure	500 psig
Design temperature	665° F
Flow sections:	
Full	20 in. od, sch. 40 or 0.593 in. wall thickness
Half	14 in. od, sch. 40 or 0.437 in. wall thickness

Steam from Reheater

Material	Alloy steel; A-158-51T-P11; 1-1/4% Cr, 1/2% Mo
Design pressure	470 psig
Design temperature	1003° F
Flow sections:	
Full	20 in. od, sch. 80 or 1.031 in. wall thickness
Half	16 in. od, sch. 80 or 0.843 in. wall thickness

Heating, Ventilating & Air Conditioning

Powerhouse

Building heating	18,200 lb steam per hr
Air preheating	228,000 lb steam per hr
Ventilating air	4,187,000 cfm supplied; 2,472,000 cfm exhausted
Air conditioning	Control rooms, 75 tons; shift engineer's office, 3 tons; packaged unit type; manufactured by Worthington Corp.

Service Bay (shop area)

Heating	1400 lb steam per hr
Ventilating air	65,800 cfm supplied; 102,500 cfm exhausted
Air conditioning (storekeeper's office)	5 tons; packaged unit type; mfd by Nevinger Mfg Co., Inc.

Service Bay (office area)

Heating	2270 lb steam per hr
Ventilating air	18,900 cfm supplied; 44,800 cfm exhausted
Air conditioning	104 tons; built-up, central water chilling system; manufactured by York Corp.

COAL HANDLING FACILITIES

Delivery

Barge

Harbor	3455 ft long, 9-ft navigable depth
Unloading dock	3160 ft long; sheet pile cells interconnected by steel girders and truss-type walkways
Unloading cranes	No. 1, mfd by Dravo Corp., 9-ton clamshell bucket by Industrial Brownhoist; No. 2, mfd by Lakeside Bridge & Steel Co., 9-ton clamshell bucket by Blaw-Knox Division; each crane has a capacity of 900 tons free digging (600 tons net) per hour and is equipped with barge shifting system
Handling method	From barge by bucket crane to receiving hopper; to belt conveyors; to crusher plant; to bunkers or storage

Delivery--Continued

Rail

Trackage	20.3 miles incl yards and all permanent tracks
Storage yards	Capacities: loaded yard, 420 cars; empty yard, 340 cars; interchange yard, 480 cars; cars move by gravity from dumper to empty storage with speed controlled by a friction-type electronically operated retarder system, fully automatic and with optional manual control, mfd by General Railway Signal Co.
Locomotives	Two 80-ton diesel-electric, manufactured by General Electric Co.
Rotary car dumper	Maximum capacity, 70-ton car: eighteen 50-ton cars per hr; manufactured by Heyl & Patterson, Inc.
Scales	Capacity, 325,000 lb; platform size, 13 by 56 ft; manufactured by Fairbanks, Morse & Co.

Crushing, Storage & Conveying

Structures

Hopper building	Reinforced concrete substructure; steel frame 62 by 68 ft by 35 ft high
Sample preparation building	North side of hopper building; steel frame, flat roof, 19 by 69 ft by 12 ft high
Surge hopper building	Steel framing 24 by 34 ft by 71 ft high
Crusher building	Reinforced concrete substructure, steel frame 60 by 76 ft by 63 ft high
Architecture:	
Hopper, surge hopper, and crusher buildings	Steel frame, gray face brick base with insulated (surge hopper uninsulated) maroon asbestos-protected steel V-beam siding above, steel sash, aluminum windows in conveyor control room
Conveyors	Uninsulated maroon asbestos-protected steel V-beam siding, uninsulated black asbestos-protected corrugated steel roofing sheets
Heating and ventilating, hopper, sample preparation, and crusher buildings	317 kw; 42,500 cfm
Air conditioning, hopper and sample preparation building	17.4 tons; built-up direct-expansion system; mfd by the Trane Co.

Crushing

Method	By "Flextooth" crushers, run-of-mine to 1 [illegible]/4-in. ring size
Crushers	2; 700 tons per hr each; manufactured by Jeffrey Mfg Co.

Storage

Yard:	
Area	61.4 acres
Capacity	1,450,000 tons (97-day supply, 25 ft high)
Mobile equipment	2 No. HD20 Allis-Chalmers 175-hp crawler tractors with No. CD203 Gar Wood angledozer blades; 1 LeTourneau-Westinghouse 275-hp, rubber-tired Tournatractor with angledozer blade; 1 No. 16TDT Euclid 190-hp, twin-engine, rubber-tired tractor-scraper; 1 MRS-190 275-hp, single-engine, rubber-tired tractor; 2 MRS-200 300-hp, single-engine, rubber-tired tractors; 3 B250 Bucyrus-Erie 22-cu-yd, rubber-tired scrapers; 1 type OS-260A Wo[illegible]ridge 30-35-cu-yd, rubber-tired scr[illegible]

Dust Collectors

Number, type, and location	1; wet type; in crusher building
Capacity	16,000 cfm
Manufacturer	American Air Filter Co., Inc.

Crushing, Storage & Conveying--Continued

Conveyor System

Manufacturers:	
Belt conveyors	Link-Belt Co.
Belts	Goodyear Tire & Rubber Co. and B. F. Goodrich Co.
Vibrating feeders and grizzlies	Jeffrey Mfg Co.
Belt weighing scales	Fairbanks, Morse & Co.
Principal equipment features:	
Belts to bunkers	2 systems
Reclaiming hoppers	2
Stocking-out conveyors	1

Belt widths and capacities:	Width, inches	Capacity, tons per hr
Car dumper to crusher building	54	900
Surge hopper to crusher building	54	1200
Barge unloaders to surge hopper	48	900 each
All others	42	700

Electrical Features

Equipment voltage rating	4160-volt board for [illegible]50-hp motors; 480-volt board for smaller motors
Control	Central control room for coal crushing, storage, and conveying equipment
Control board manufacturer	Allis-Chalmers Mfg Co.

WATER SUPPLY

Circulating Water for Condensers & Raw Water System

General Data

Source	Ohio River
River stages (pool of Dam No. 53 at Grand Chain)	Extreme minimum, El. 288; maximum, El. 345; normal minimum, El. 290
Flow	112,000 gpm per unit; 1,120,000 gpm for 10 units
Treatment	Chlorinated to inhibit slime growth

Intake

Channel	Excavated, about 2000 ft to Ohio River
Structure:	
Type	Reinforced concrete, 53 by 338 ft by 70 ft high, about 400 ft north of powerhouse
Heating and ventilating	145 kw; 30,000 cfm
Trashracks	2 per unit, 12 ft 8 in. wide by 21 ft high
Traveling screens	2 per unit, 10 ft wide; manufactured by Link-Belt Co.
Circulating pumps	2 per unit; vertical mixed-flow type; 600-hp, 322-rpm motor; 56,000-gpm capacity; 35-ft head; manufactured by Worthington Corp. with Westinghouse motors
Gantry crane	30-ton capacity; manufactured by Milwaukee Crane & Service Co.

Conduits

Intake	10; 78-in.-diam reinforced concrete pipe; total length, 4624 ft
Discharge	10; 78-in.-diam reinforced concrete pipe; total length, 6601 ft
Manufacturer	Lock Joint Pipe Co.

Discharge

Structure	Reinforced concrete headwall with stoplog guides about 500 ft north of powerhouse
Channel	Excavated, about 2500 ft to Ohio River; minimum water elevation in channel controlled by steel sheet pile cellular weir adjacent to river

Chlorinator Building

Type	Steel frame structure, 50 by 57 ft by 19 ft high
Chlorine storage	Tank car or ton containers
Chlorinators	2; 6000 lb per day with evaporators; automatically operated on intermittent program control
Architecture:	
Open structure	Steel frame with maroon asbestos-protected steel V-beam siding and corrugated glass
Low-level area	Exposed steel frame, gray brick walls, steel sash
Heating and ventilating	52 kw; 4000 cfm

Water Treatment Plant

Structure

Type	Reinforced concrete substructure, 51 by 67 ft by 37 ft high
Architecture	Exposed structural steel frame, gray face brick exterior walls, aluminum windows
Heating and ventilating	113 kw; 34,700 cfm

Equipment

Settling basins	4; 23,040-gal effective capacity each; 4-hr retention
Filters	4; 48-sq-ft size; 96-gpm capacity each
Storage wells	Filtered, 42,800 gal; softened, 24,000 gal; domestic, 10,650 gal
Pumps:	
Raw water supply	3 of 200-gpm cap. @ 100-ft head
Filter wash water	1 of 720-gpm cap. @ 32-ft head
Softener supply	3 of 160-gpm cap. @ 50-ft head
Soft water service	3 of 160-gpm cap. @ 298-ft head
Domestic water supply	2 of 40-gpm cap. @ 20-ft head
Domestic water service	2 of 150-gpm cap. @ 160-ft head
Softening	Zeolite system; manufactured by Hungerford & Terry, Inc.; capacities: 320 gpm at design rate, 4280 kilograins of hardness removed between regenerations, 4 tanks

CONTROL BUILDING

Structure

Location	Adjoining switchyard south of powerhouse, opposite unit 5
Type and dimensions:	
Substructure	15-ft-deep concrete basement, monolithic walls and slab
Superstructure	Steel framing 60 by 130 ft by 25 ft high
Architecture	Gray face brick base with insulated maroon asbestos-protected steel V-beam siding above; exposed steel frame and gray face brick walls for low-level office area; aluminum windows
Heating and ventilating	141 kw; 25,500 cfm
Air conditioning	30-ton-capacity, built-up direct expansion system, mfd by Worthington Corp.

Switchboards

Arrangement	Instruments, recorder, automatic load control, d-c boards and benchboard in control room; duplex-type relay boards in separate room
Manufacturer	Allis-Chalmers Mfg Co.

TRANSFORMERS

Main Power

Number and type	10; FOA (forced oil, forced air cooled), 3 ph
Rating	17.1-161 kv, 170,000 kva
Manufacturer	General Electric Co.

Common Auxiliary Power

Number and type	2; OA/FA (oil immersed, air cooled/forced air cooled), 3 ph
Rating	161-4.16 kv, 20,000/25,000 kva
Manufacturer	General Electric Co.

Unit Auxiliary Power

Number and type	10; OA/FA (oil immersed, air cooled/forced air cooled), 3 ph
Rating	17.1-4.16 kv, 9,000/11,250 kva
Manufacturer	Westinghouse Electric Corp.

SWITCHYARD

161-Kv Yard

Bays	26, including 13 line
Conductors	Aluminum tubing, welded construction
Disconnect switches	1600-63,000 amp momentary, 1200-63,000 amp momentary, 1200-42,000 amp momentary; mfd by Delta-Star Mfg Co.
Oil circuit breakers	Ten 1600 amp, 10,000,000 kva interrupting capacity, 3/20 cycle reclosing; thirteen 1200 amp, 10,000,000 kva interrupting capacity, 3/20 cycle reclosing; mfd by Westinghouse Electric Corp.

OTHER ELECTRICAL FEATURES

Cables

Power:	
5-kv	Single conductor, AVCSB (asbestos and varnished cambric insulated, shielded, asbestos braided) and ROSJ (ozone resisting, rubber insulated, shielded, rubber jacketed)
600-volt	Single conductor, AVA (asbestos and varnished cambric insulated, asbestos braided) and ROJ (rubber insulated, rubber jacketed) and multiconductor MI (mineral insulated)
Control:	
600-volt	Multiple conductor, ROJJ (rubber insulated, rubber jacketed, overall jacketed)

Lightning Arresters

Rating, 161-kv circuit	145 kv maximum line to ground
Manufacturer	General Electric Co.

Communication Systems

Telephone	PAX, manual, line carrier, microwave and radio
Printer telegraph	Microwave
Paging and intercommunication	Powerhouse area
Telemetering	Line carrier and microwave
Automatic load control	Line carrier

Illumination

System	Single phase, 220/110 volts
Turbine room	Incandescent high bay units
Boiler house	Firing aisle, industrial fluorescent; other areas, incandescent
Control building	Control room, indirect incandescent; other areas, fluorescent
Service bay	Mostly fluorescent
Yard	Incandescent for coal handling, street lighting, and flood lighting; 13 flood light towers 100 ft high with bank of 1500-watt floodlight units totaling 70 lamps and 105 kw in coal storage yard

OTHER BUILDINGS & YARD FEATURES

Buildings

Storage	Concrete block base with steel framing and uninsulated asbestos-protected steel above; 61 by 202 ft by 27 ft high; equipped with Austin-Western 4-ton, rubber-tired mobile crane
Utility	Exposed structural steel frame, gray face brick exterior walls, blue corrugated glass high-level windows; repair shop area, 60 by 120 ft by 28 ft high with 8 exterior rolling steel doors
Carpenter shop	At south end utility building, steel frame, flat roof, 20 by 40 ft by 12 ft high
Heating and ventilating	336 kw: 93,000 cfm

Yard

Ash disposal area:	
Location	West of and adjacent to coal storage yard
Area	145 acres
Capacity	140 unit-years
Future area	To the west of initial area
Mobile equipment	One 20-ton Bucyrus-Erie No. 22B rubber-tired crane, diesel powered, 3/4-cu-yd Erie-Strayer bucket, for general yard service
Parking areas	Capacity, 300 automobiles
Miscellaneous	Radio antenna and anemometer tower on top of water tank

LIMESTONE SYSTEM STATISTICS

LIMESTONE RECEIVING EQUIPMENT

Car Unloaders (Two)

Manufacturer	Barber-Greene
Model	No. 358
Belt Width	24 inches
Belt Speed	100 F.P.M.
Rated Capacity	120 tons/hr. max.; 80 tons/hr. min.
Motor	5 hp, 1730 rpm, Westinghouse

Conveyor, Stocking-Out

Manufacturer	Continental
Model	
Belt Width	24 inches
Belt Speed	500 F.P.M.
Rated Capacity	120 tons/hr.
Motor	20 hp, 1755 rpm, Westinghouse

Conveyor, From Truck Hopper to Receiving Hopper

Manufacturer	Barber-Greene
Model	No. 76
Belt Width	18 inches
Belt Speed	
Rated Capacity	120 tons/hr.
Motor	10 hp, 1735 rpm, Westinghouse

Belt Feeder

Manufacturer	Barber-Greene
Model	No. 432
Belt Width	18 inches
Belt Speed	
Rated Capacity	25 tons/hr. max.
Motor	1 hp, 1750 rpm, Marathon

Truck Hopper

Capacity	5 cubic yards

Receiving Hopper

Capacity	40.8 tons or 20 tons/hr.

LIMESTONE DRYING EQUIPMENT

Dryer

Manufacturer	Hardinge Company
Type	Class X H-10, Oil-Fired, Concurrent Flow
Size	70" I.D. X 45'-0" Long
Capacity	20 tons/hr. of minus 1-1/2 inch stone
Shell Speed	6.1 rpm
Motor	30 hp, 1185 rpm, Westinghouse
Speed Reducer	Falk No. 2080 - YZ, Double Reduction, 23.51 to 1 Ratio

Combustion Chamber

Manufacturer	Hardinge
Rated Capacity	14.5 million btu/hr. max.

Automatic Burner

Manufacturer	York-Shipley, Inc.
Type & Size	FA - 350
Firing Rate	104 G.P.H.

Fuel Oil Pump

Manufacturer	York-Shipley, Inc.
Model	No. 300
Rated Capacity	104 G.P.H.
Motor	3/4 hp, 1725 rpm, General Electric

LIMESTONE GRINDING EQUIPMENT

Bucket Elevator

Manufacturer	Link-Belt
Type	No. 1
Rated Capacity	30 tons/hr.
Motor	3 hp, 1800 rpm

Surge Tank

Rated Capacity	1000 cubic ft.; 48 tons; 20 tons/hr.

C.V. Volumetric Belt Feeder

Manufacturer	Hardinge
Rated Capacity	30 tons/hr.
Motor	1/2 hp, variable speed, Dyna

Ball Mill

Manufacturer	Hardinge
Type & Size	Conical Ball Mill, 10'-0" Dia. X 72" Cylinder Length
Shell Speed	18 rpm
Counter-Shaft Speed	154 rpm
Rated Capacity	20 tons/hr. @ Hardgrove Grindability Index of 50
Product Fineness	Up to 80% Minus 400 Mesh @ rated capacity and Grindability Index 50
Grinding Media	Forged Steel Grinding Balls
Motor	450 hp, 1170 rpm, Westinghouse
Speed Reducer	Falk No. 1135 YFI, Single Reduction - Parallel Shafts, 7.609 to Rated

Gyrotor Classifier

Manufacturer	Hardinge
Size	No. 108
Motor	10 hp, 38-190 rpm, Sterling Electric

Electric Ear

Manufacturer	Hardinge
Model	T

Air Blower

Manufacturer	Chicago Blower
Size	No. 16-1/2 SQA FBAK
Motor	15 hp, 3520 rpm, General Electric

Air Compressor

Manufacturer	General Electric
Type	K
Rated Capacity	8.3 cfm
Motor	1-1/2 hp, 1720 rpm, General Electric

Dryer Exhaust Fan

Manufacturer	Clarage
Size & Type	121 X L
Rated Capacity	9500 cfm @ 1411 rpm & 33.9 bhp
Rated Static Pressure	10.2 in.-H_2O
Rated Temperature	260°F.
Motor	30 hp, 1800 rpm, Westinghouse

Dryer Exhaust Cyclone Dust Collector

Manufacturer	Ducon Co., Inc.
Type	SDM
Size	250
Rated Capacity	9500 cfm @ 1411 rpm & 33.9 bhp

Circulation Fan

Manufacturer	Clarage
Type & Size	133 XL
Rated Capacity	25,000 cfm @ 1110 rpm & 111.3 bhp
Rated Static Pressure	18.8 in.-H_2O
Rated Temperature	200°F.
Motor	125 hp, 1775 rpm, Westinghouse

LIMESTONE STORAGE EQUIPMENT

Storage Tank

Rated Capacity	6600 cubic ft.; 316.8 tons; 20 tons/hr.

Cyclone Dust Collector

Manufacturer	Ducon Co., Inc.
Type	SDM
Size	650
Rated Capacity	25,000 cfm

Transport Pump

Manufacturer	Fuller-Kinyon
Type	H2S, 7"
Rated Capacity	30 tons/hr.
Motor	30 hp, 1170 rpm, Reliance

Air Compressor

Manufacturer	Fuller-Kinyon
Type	C110
Discharge Pressure	27 psig max.
Motor	50 hp, 710 rpm, Reliance

Dust Collector

Manufacturer	Mikro-Pulsaire
Model	64S - 8 - 20
Motor	10 hp, 1760 rpm

LIMESTONE INJECTION EQUIPMENT

Feed Tank

Rated Capacity	3000 cubic ft.; 14.4 tons; 20 tons/hr.

Dust Collector

Manufacturer	Flex-Kleen
Model	84 CT 30

Screw Conveyors

Manufacturer	Link-Belt
Size	9" Dia.
Speed	46.3 rpm max., 4.6 rpm min.
Motor	3 hp, 1800 rpm, Reeves

Rotary Seal

Manufacturer	Detroit Stoker Co.
Size	10"
Speed	22 rpm max., 2.2 rpm min.
Motor	3 hp, 1800 rpm, Reeves

Transport & Injection Air Compressors

Manufacturer	Allis-Chalmers
Model	11S
Discharge Pressure	20 psig.@ 67 bhp
Motor	50 hp, 875 rpm, Allis-Chalmers

APPENDIX B

WATER-COOLED PROBE DEVELOPMENT

To obtain data across the Planes A-A and B-B it was necessary for TVA to develop moveable, water-cooled probes. The probes had to be capable of extended periods of insertion in the furnace in order to obtain gas temperatures, pitot pressure measurements, and also to secure dust from the gas by isokinetic sampling. Probes had to be totally supported outside the furnace, much like sootblowers. A total of 14 probes plus spares were required. All probes were constructed at TVA's Service Shops, Muscle Shoals, Alabama.

Each probe required (1) water supply for cooling, (2) compressed air to operate aspirator used in dust sampling, (3) 32-volt power for dust tube heat tracing, (4) thermocouple lead wire, (5) tubing for pitot measurement, (6) probe drive power cable, (7) manometer for aspirator control settings. Items 1 through 5 were arranged in umbilical fashion.

A section view through a probe is shown in Figure B-1. Probes were 29 feet for the east side and only 26 feet on the west side because of interference with the powerhouse endwall. Type 316 stainless steel tubing, 2-1/2 inches in O.D. served as outer structural member with a top fin welded to guide movement through support rollers and add strength.

Movement was by a chain drive attached to the cold end of probe. This proved generally satisfactory because when occasional binding occurred the drive pin would shear thus preventing a more serious rupture elsewhere. Guidance adjacent to the boiler was by top and bottom rollers while at the probe drive end a wheel-in-track was used. Only the lowest probe (Station 6) in Plane B-B required guidance and suspension somewhat different.

Considerable development effort was required at the dust inlet hole where slag wanted to stick. This problem was finally solved by a toroidal ring through which small holes were drilled allowing air to jet outward and keep the nozzle slag free. Account was taken of this air which would subsequently be ingested with the dust sample.

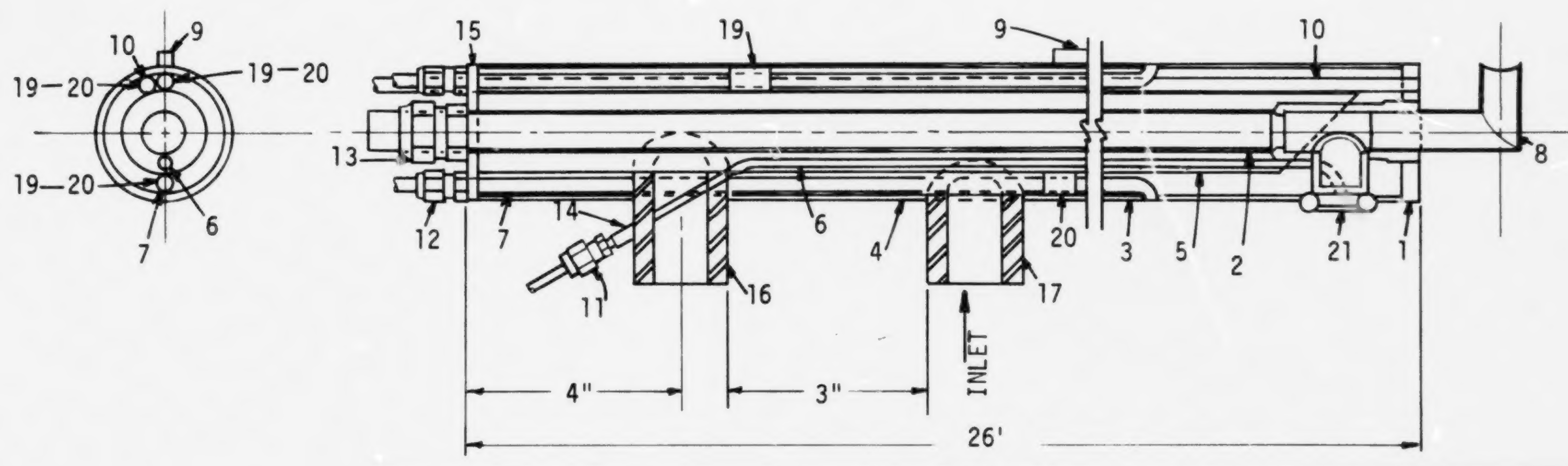
Considering the hundreds of hours during which these probes were in the furnace they proved capable of obtaining the desired results. Experience led to satisfactory maintenance procedures and no major problems were encountered.

Detailed procedures employed in the use of these probes are covered in the sampling writeups for Stations 4 thru 7, in Appendix C. Of course, the purpose of taking dust samples was to determine the amount of sulfur pickup and relative proportions of fly ash and lime. Sulfur dioxide content of gas at Plane A-A was determined by a wet chemical technique using an H_2O_2 scrubber and titrating the reacted solution with NaOH. Oxygen levels in Plane A-A were measured with a Beckman Field O_2 analyzer connected to the water-cooled probe outlet.

In figure B-2 are shown the four water-cooled probes located on the west side of unit 10 at Plane A-A. The motor and gearbox for the chain drive of each probe are shown in figure B-3. Note the water cooling hoses and dust collection equipment attached to the end of each probe. A two-man team normally operated each probe and its associated instrumentation.

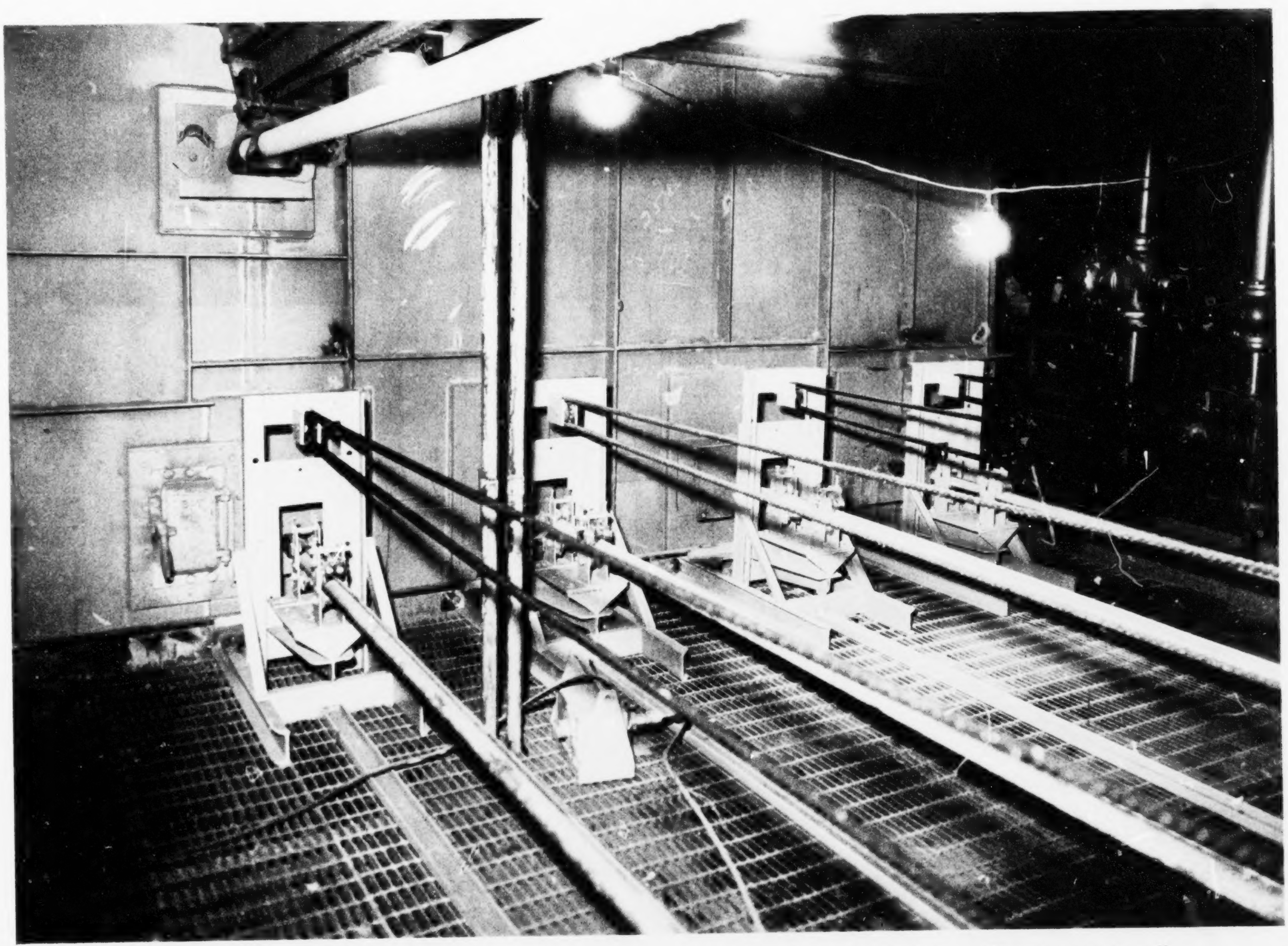
FIGURE B-1

SECTION VIEW OF 2½" WATER-COOLED PROBE



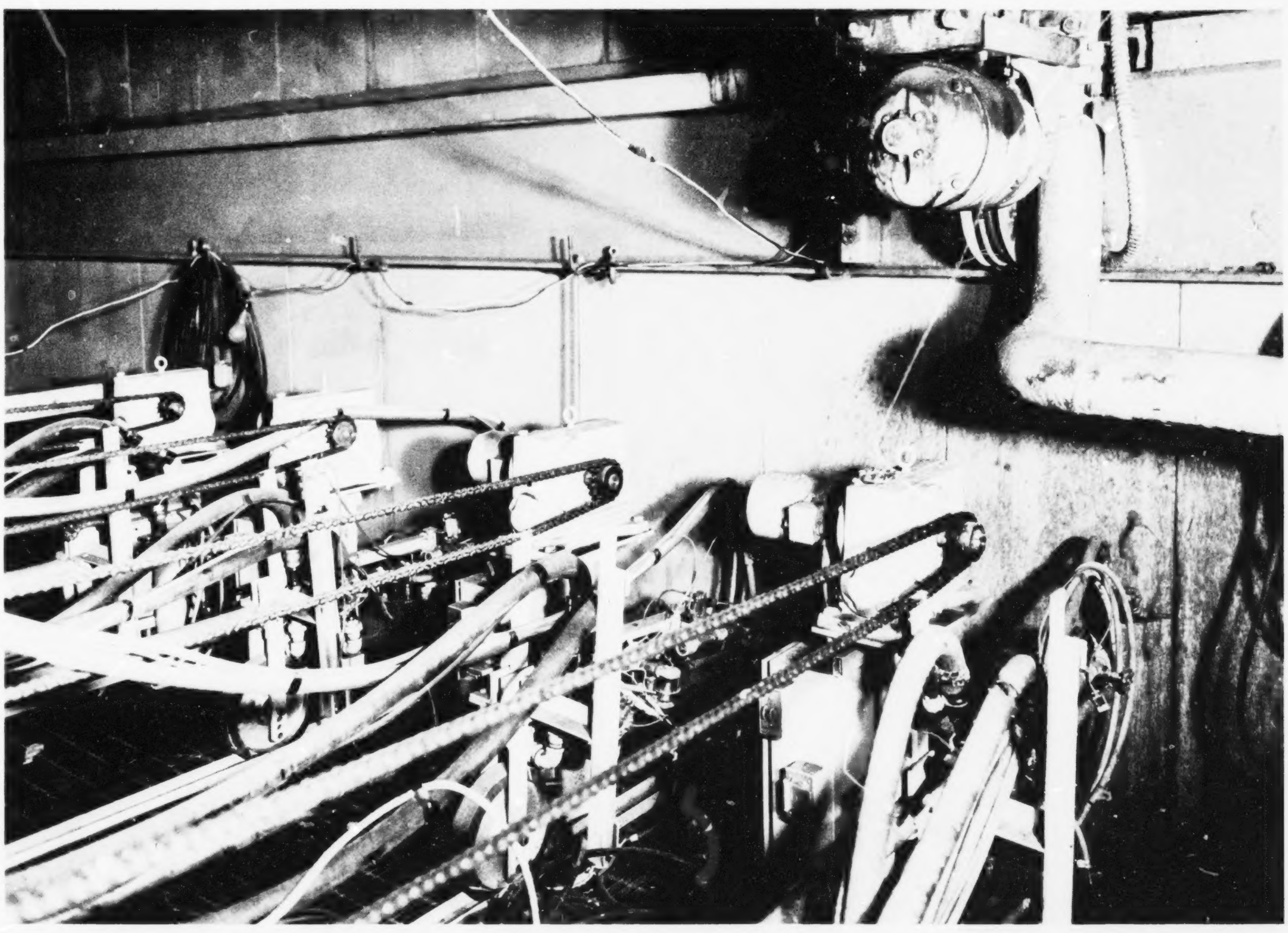
BILL OF MATERIAL			
PART NO	PART NAME	MATERIAL	DESCRIPTION
1	Probe Head	Stainless Steel	Ref Dwg SA 133
2	Water Jacket, Inner	" "	3/4" O.D.x.035"wall x 26'
3	Water Jacket, Outer	" "	2 1/2" O.D.x.065"wall x 12'
4	Water Jacket, Outer	" "	2 1/2" O.D.x.188"wall x 14'
5	Water Baffle Tube	" "	1 1/2" O.D.x.035"wall x 25'-115/8"
6	Tubing	Copper	3/16" x.035"wall x 31'
7	Tubing	Stainless Steel	1/4" x.049"wall x 28'-2"lengths
8	3/4" Nozzle	" "	Ref Dwg SA 155
9	Fin	" "	1/4"x1/4x 24'-31/8"long
10	Tubing	" "	1/4"x.028"wall x 27'-3"
11	Swagelok	" "	1/4"tube to1/8"male pipe thread
12	Swagelok	" "	1/4"tube to1/4"pipe
13	Swagelok	" "	3/4"tube to buttweld fitting
14	Coupling	Stainless Steel	1/8"pipe coupling
15	End Plate	Carbon Steel	2 1/2"O.D.x 1/4"
16	Cooling Water Outlet	" "	1" pipe coupling
17	Cooling Water Inlet	" "	" "
18	Plug	" "	" "
19	Spacer	Stainless Steel	7/16"O.D.x.0625" wall x 1"lg.
20	Spacer	" "	3/16"O.D.x.0625"wall x 1"lg.
21	Air Ring	" "	Ref Dwg SA 125

FIGURE B-2



Limestone Injection System (SO_2 Removal) - Test probe on "B" side of unit number 10 boiler. (Showing nozzle end)

FIGURE B-3



Limestone Injection System (SO_2 Removal) - Test probe on "B" side of unit number 10 boiler.
(Showing drives and other test equipment on the probe.)

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APPENDIX C

TESTING, SAMPLING, AND ANALYTICAL PROCEDURES

1. General

Dust samples taken during the test program were analyzed in two categories. The first provided rapid information for daily evaluation of test results and the second catagory provided information on samples requiring time consuming analyses. The first category work was done at Shawnee's field test laboratory trailer; the second at TVA's Power Service Center chemical laboratory in Chattanooga.

2. Sample Preparation and Processing

Sample Station 1 - Coal (See figure 11 repeated on page C-32.)

Coal samples were taken continuously during each test from each of the four coal scales of unit 10. These generated a single composite sample for a single test. The composite was crushed to 1/4 to 0 inch and then two 1-quart portions riffled out. Identification of the sample conforms to test numbers. One quart was pulverized for the field laboratory for the determination of sulfur. The second quart was air dried, riffled, and pulverized to fill two 2-ounce bags. One 2-ounce portion was a holdback sample retained at the field laboratory. The second 2-ounce portion was sent to the plant laboratory for proximate determination, with the exception of every fourth sample which was sent to the Chattanooga laboratory for proximate, ultimate, and ash-fusion determination. In addition, sulfur forms and ash composition were determined on every tenth sample.

In order to provide hourly information on sulfur fluctuations in the coal, grab samples (1 quart each scale composited every hour) were crushed, riffled, and a 60-gram portion pulverized and sent to the field laboratory. This portion was held back for 10 tests and then discarded.

Sample Station 2 - Bottom Ash

These ash samples were expected to provide little information. One composited grab sample was collected from the east and west furnace bottoms through a manhole access. Each sample was divided into two half-gallon containers, prepared and sent to the field laboratory for determination of calcium and sulfate content. The samples consistently contained very low (0.5%) SO_2 and (5.0%) CaO.

Sample Station 3 - Limestone

As Received Limestone.

One grab sample of 25 pounds a shipment was crushed to 1/4 by 0 inch and riffled into two 1-quart containers, one going to the field laboratory and one to the Chattanooga laboratory. Calcium and moisture content were determined in the field laboratory; particle size and complete assay were run in the Central Laboratory.

Pulverized Limestone.

Samples of pulverized limestone were taken from the feed tank by means of a pipe-thief with several openings along its lower portion to admit representative stone. The particle size index was determined on each daily composite using the Fisher Sub-Sieve Sizer. Calcium content was also run in the field laboratory. Particle size distribution was determined for a selected five samples in the Central Laboratory and a complete assay on a daily composite for every tenth test.

Sample Stations 4, 5, 6, and 7 (East and West)

Velocity, Temperature and Dust Sampling Probes

Water-cooled probes were positioned to obtain the subject samples at each of 48 points in Plane A-A (or 36 points in Plane B-B). Each point was the center of equal areas 3' x 4' for which velocity and temperature measurements were taken for determination of isokinetic sampling rate conditions. Dust sampling initially was 15 minutes per point but was later reduced to 2-1/2 minutes to permit obtaining a full traverse in approximately 20 minutes. The few grams of dust collected in preweighed jars inserted into each probe (1 jar per point) provided enough for field lab determination for weight, and content of calcium, sulfur and carbonate. The remaining portion of each sample was stored for project duration. Refer to Figure 22 for Plane A-A layout.

More specific details on probe sampling are covered in Procedures, below.

Sample Station 8 - Boiler Outlet Plane C-C

Dust, O_2 and SO_2 were sampled by probes as shown in the configuration Figure 24. Six points were sampled continuously for dust during testing to generate one composite sample per side per test. A small portion (about 60 g.) was split out for field quantitative determination of calcium, sulfur and qualitative determination of carbonate. The remainder was shipped to the Central Lab where particle size distribution and complete assay were made on every tenth sample if results indicated the need. The sampling probe was 3/4-inch diameter and was equipped with the same type sample jars as for the water-cooled probes. Each sample was of 15 minute duration.

A fixed sampling system was installed for SO_2 measurements; the composite flow samples from east and west sides were continuously measured by UV analyzers on each side. Originally, the heat traced sample lines were of 316 stainless steel but they failed by apparent stress corrosion cracking. These lines were replaced by an all teflon tubing system which operated satisfactorily. O_2 sampling was accomplished by probes inserted into the same ports as dust sampling probes.

See Procedures for more details.

Sample Stations 9, 11, and 12 - Dust

These locations were for dust sampling during periods of evaluation of mechanical collectors and precipitators. They conformed to standard procedures for such sampling locations and are covered in Appendix F.

Sample Stations 10 and 13 - Fly-Ash Hoppers

Fly ash samples from mechanical collector and precipitator hoppers were obtained in the dry state from sluice lines upstream of hydroveyors during selected tests. CaO and SO_2 were normally determined on these samples. Bulk samples were made available to investigators seeking possible end use of the fly ash - limestone mixture.

3. Detailed Sampling Procedures

Coal Sampling (Station 1)

a. Equipment Required

1. Coal scoop
2. 5-gallon cans with lids, 8 required
3. Crusher
4. Riffles

b. Sampling Location

At unit 10 Richardson coal scales on elevation 345.

c. Sampling Procedure

Samples were obtained from each of the four (4) coal scales sequentially and repetitiously. The samples from each scale were deposited in a 5-gallon can. There was one bucket per scale. There should be a minimum of 5 gallons of coal sampled per scale per test, or a total of 20 gallons of raw coal. At the conclusion of a test, the total aggregate samples were crushed to 4 mesh, composited, and riffled into two quarts and clearly identified. Of these two quarts, one quart went to the field laboratory for sulfur analysis and holdback. The other quart was air dried, by plant personnel, to determine the air-dried moisture loss. This sample was crushed to 60 mesh and riffled to two ounce samples and packaged for shipment to the Central Laboratory for proximate or ultimate analysis and possible ash fusion, sulfur forms, and ash compositions analysis.

d. Sample Identiticiaton

The raw coal samples were labeled immediately after the initial riffling to two quart increments as to time, test number, and test date.

Sample Processing and Storage

There was a variety of samples—coal, limestone, fly ash, bottom ash, etc.—which needed to be prepared for analysis, stored, and then distributed for the various analyses. After processing, the samples were placed in an area designated f[illegible]mple storage.

Bottom Ash Sampling (Station 2)

a. Equipment Required

1. Long handled shovel
2. 2-1/2-gallon Mason jars per test

Sampling Location: Basement of Unit 10

The sample was obtained through the access doors on the furnace ash sluice hopper, north end on both east and west sides.

b. Sampling Procedure

With the shovel placed through the access door samples of slag were obtained from several spots atop the pile on north end only. This was done about midway in the test period and reduced to 2 half-gallon samples.

c. Sample Identification

The bottom-ash samples were identified immediately after collection according to sample type, sample location, test number, and test date.

d. Sample Analysis and Storage

Immediately after being properly identified, the samples were carried to the Field Laboratory where they were analyzed and stored or packaged for transportation to the Central Laboratory. Because of the small value of results obtained from bottom ash samples they were soon dropped from the procedure.

Limestone Sampling (Station 3)

Raw Limestone

a. Equipment Required
   1. Shovel
   2. One-gallon can w/lid
   3. Labels

b. Sample Location

Stone was taken from several points in the truckload dumped into the receiving hopper.

c. Sample Identification

Cans were identified by labels applied immediately after collection according to location, date and time of samples.

Pulverized Limestone

a. Equipment Required (See Figure C-1).

1. Sampling thief - This device consisted of 2 concentric pieces of pipe with a series of 12 holes spaced 7 inches apart so that when forced into the limestone pile the stone would enter the holes. Rotation of the outer pipe resulted in covering the holes and securing the sample. The counter balanced thief was then withdrawn, bottom plug removed and sample discharged into can.

2. One-gallon cans w/lids
3. Labels

b. Sample Location

Representative samples were obtained during each test from limestone withdrawn by the thief from atop the feed tank located inside the powerhouse.

c. Sample Identification

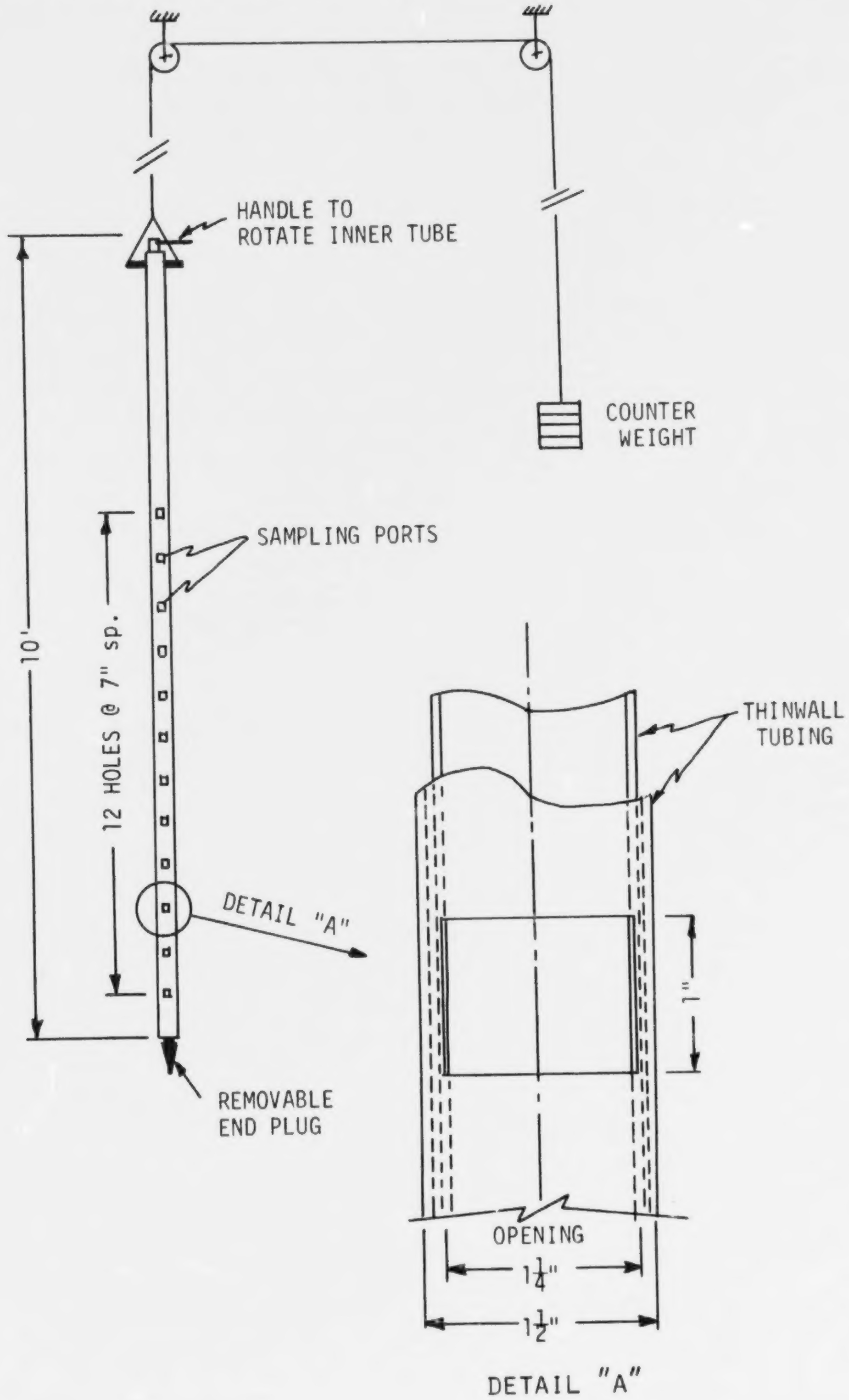
Samples are labeled immediately after collection according to type stone, sample location, test number and test date.

Temperature, Velocity, and Dust Sampling (Stations 4, 5, 6, and 7)

a. Equipment needed
   1. Water-cooled probe with attachments for temperature traverse, velocity pressure traverse, and dust sampling.
   2. Elapsed time stopwatch.
   3. Slide rule.
   4. Instruction book and sampling rate tables.
   5. Sample collector (preweighed glass jar).

FIGURE C-1

SAMPLING THIEF FOR LIMESTONE AT FEED TANK



6. Channellock pliers.
7. Wire brush.

b. Sampling procedure

Temperature, velocity, and dust traverses were run using either the eight probes at the Plane A-A or the six probes at the vertical plane behind the first bank of superheater tubes, Plane B-B. After obtaining temperature and velocity, a sampling rate was computed that was equivalent to an average isokinetic sampling at the nozzle. Each measurement required less than 1/2 minute to obtain.

The following procedures were used for:

Temperature traverse

The temperature traverse was made with a shielded platinum, platinum-10% rhodium thermocouple inserted into the water-cooled probe with the thermocouple leads running to a Speedomax recorder (Figure C-3). Before beginning the temperature traverse, the recorder must be standardized and the probe must be prepared.

Instrument check:

1. Mark date, test number, probe number, test points, and observers' names on both data sheets (see Figures C-4, C-5).
2. Open the recorder door (see Figure C-6) and turn the toggle switch located inside the recorder to the "On" position. The recorder should be left on for the duration of the sampling.
3. Place switch (A) in the "short" position.
4. Turn "span calibrate knob" (red inner knob) to the fully counterclockwise position.
5. Turn "Zero MV Control" to zero and lock.
6. Turn "Add to Zero Control" to zero.
7. Turn "Span MV Control" (black outer knob) to 25.
8. Turn "Zero Suppression" to either zero + or zero -.
9. Recorder pen should read zero. Mark Zero Check on recorder chart along with Test Number and Date.
10. Set "Add to Zero" on 10.
11. Turn chart drive switch on "fast" speed.
12. The recorder pen should read 40% of chart.
13. Return "Add to Zero" control to zero. Stop chart drive and mark "Calibration Span Check" on recorder chart.
14. Dial in with the "Zero MV" control the millivolt on a PT + 10% Rh vs. Pt thermocouple corresponding to ambient temperature (see millivolt table). Mark ambient temperature on data sheet.
15. Mark recorder span MV on data sheet.

WATER-COOLED PROBE ARRANGEMENTS

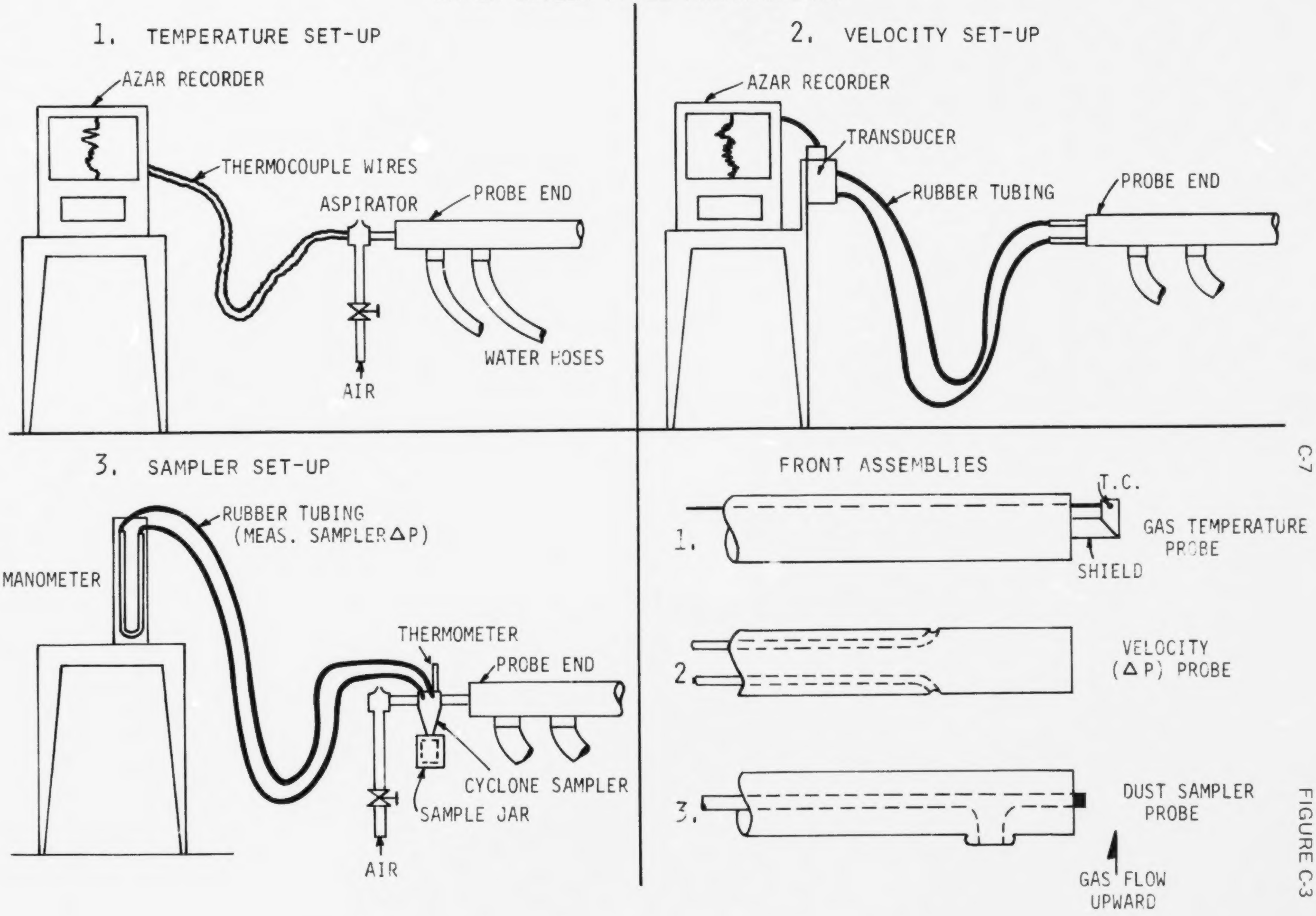


FIGURE C-3

Shawnee Steam Plant
Project 2438
Temperature and Velocity Data Sheet
Test Stations 4 - 7

Date 2/16/71
Test No. S-302
Probe No. 4 AW
Observers Daniel
King

Temperature

Time	Test Point	Recorder Reading	MV (Exhibit 3)	Temperature °F (Exhibit 4)
2:20	4 AW 1	41	10.25	1935
	2	41	10.25	1935
	3	42	10.50	1975
	4	44	11.00	2050
	5	44	11.00	2050
	6	40	10.00	1900

Ambient Temp. 85 °F

Recorder Span 25

Velocity

				Velocity Conversion (See Velocity Tables)	
Time	Point	Recorder Reading	Velocity Pressure, In H_2O (Exhibit 5 or 5A)	Ft/Min.	Ft/Sec.
	4 AW 1	61	.3050		
	2	40	.2000		
	3	47	.2350		
	4	24	.1200		
	5	24	.1200		
	6	54	.2700		
2:25					

Recorder Span 10

Remarks:

Figure C-4

SLP 7-B
(Rev. 10-15-70)

SHAWNEE STEAM PLANT
PROJECT 2438
DUST SAMPLE DATA SHEET
TEST STATIONS 4-7

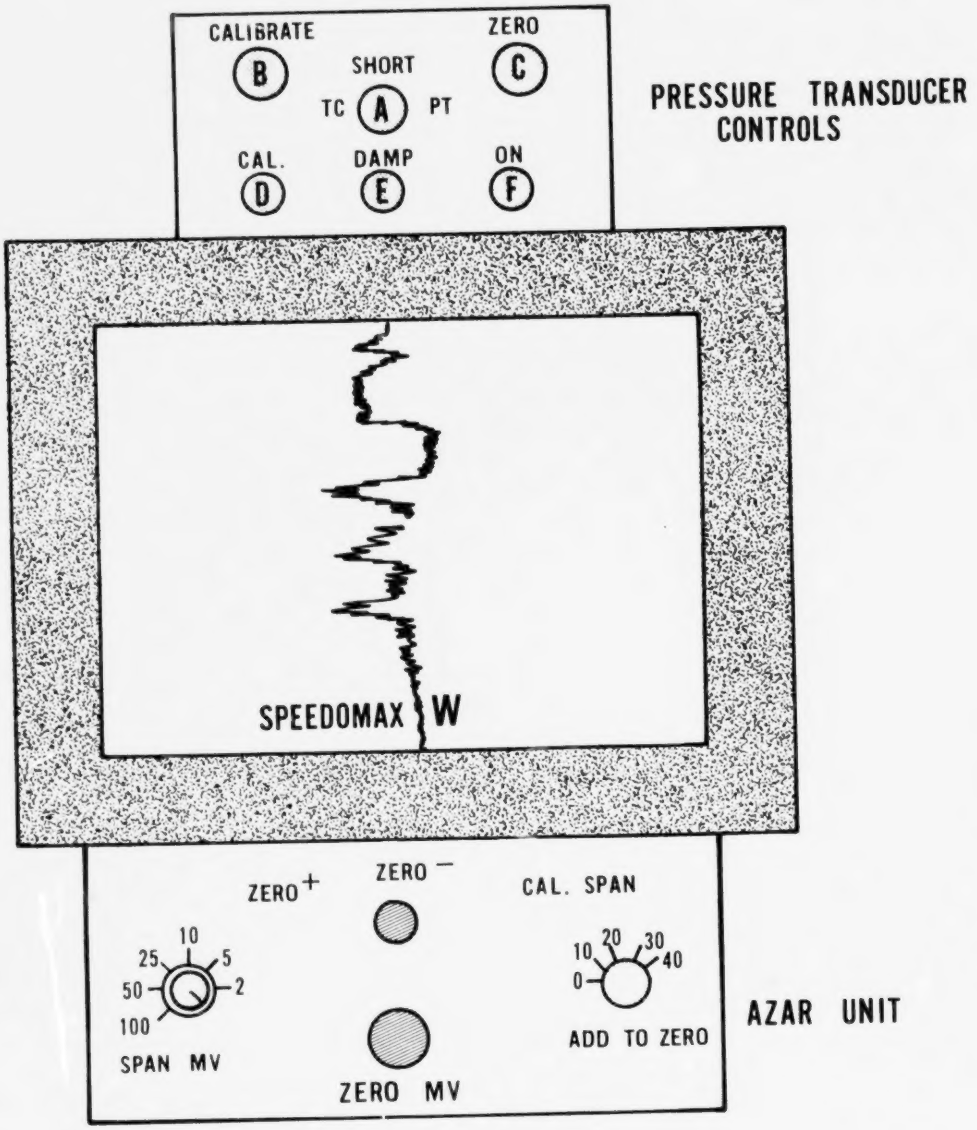
Date 2/16/71
Test No. S-302
Probe No. 4 AW
Observers Daniel
King

Time		Test Point	Static Press. At Sampler - "W.G.	Sampler Temp. °F	(1)	(2)	(1)×(2)=(3) Flue Gas CFM	(4) Seal Air CFM	(3)+(4) Sampler Total CFM	Δ P "H_2O Exhibit 8
Begin End	Elapsed Min.				Exhibit 6 Correction Factor	Nozzle CFM Sampling Rate Table				
2:40 2:42½	2½	4AW 1		160	.240	14.25	3.42	1.14	4.56	14.8
2:43½ 2:46	2½	2		160	.240	11.54	2.77	1.14	3.91	10.9
2:47 2:49½	2½	3		160	.236	12.61	2.98	1.14	4.12	11.9
2:50½ 2:53	2½	4		160	.225	9.15	2.06	1.14	3.20	7.2
2:54 2:56½	2½	5		160	.225	9.15	2.06	1.14	3.20	7.2
2:57½ 3:00	2½	6		160	.243	13.31	3.24	1.14	4.38	13.8

Probe Seal Air Setting 1.14 CFM

Figure C-5

FIGURE C-6



Ⓐ Recorder Input Selector Switch
Ⓑ Calibrate Control
Ⓒ Zero Adjustment
Ⓓ Calibrate Push Button
Ⓔ Excitation Control Switch
Ⓕ Damping Control

The above controls (B–F) are effective only when the recorder selector switch (A) is in the PT position.

Probe Check:

1. Remove the end plug from the probe and install the thermocouple shield. Position the thermocouple bead in the center of the shield opening by advancing the thermocouple 1/4 inch at a time until the bead appears from the probe channel, then 1/8 inch until centered.
2. Seal the pressure taps to the cyclone inlet and outlet.
3. Check if dust tube and sample holder are hot.
4. Water cooling -

   Is pressure gage at 50 psig or above?

   Is valve on probe open?

   The water temperature will increase as probe is moved into the boiler. If temperature exceeds 150° F (as measured by dial thermometer in outlet water) immediately withdraw probe from boiler.
5. Open the flowmeter needle valve and supply air to the dust sampling nozzle at a rate of 2 cfm.
6. Open the air supply to the aspirator and set the proper aspiration rate (about 1-1/2 turns on the valve).
7. Check air flow across thermocouple.
8. Close air supply to the aspirator.

Operation:

1. Move probe to first test point and set proper aspiration rate (wide open valve).
2. Turn chart drive on "Fast."
3. Mark starting time on both data sheet and on chart.
4. Set recorder input selector switch (A) to "TC" position for 15 seconds.
5. Return recorder input selector switch (A) to "Short" position.
6. Mark test point number on chart.
7. Move probe to next test point and repeat items (4), (5), and (6) until traverse is completed.
8. Mark stop time on data sheet and on chart.
9. Turn chart drive "Off."
10. Withdraw probe from furnace.

    Instrument operator -

    Mark average recorder readings on data sheet.

    Convert recorder readings to M.V. (Figure C-7) and enter on data sheet.

    Convert millivolts to temperature (Figure C-8) and enter on data sheet.

    Probe operator -

    Remove thermocouple shield.

    Deslag thermocouple bead.

    Retract thermocouple wire.

    Replace end plug in probe.

Figure C-7
25% Span

Rec. Rdng. %	M.V.	Rec. Rdng. %	M.V.	Rec. Rdng. %	M.V.
1	.25	31	7.75	61	15.25
2	.50	32	8.00	62	15.50
3	.75	33	8.25	63	15.75
4	1.00	34	8.50	64	16.00
5	1.25	35	8.75	65	16.25
6	1.50	36	9.00	66	16.50
7	1.75	37	9.25	67	16.75
8	2.00	38	9.50	68	17.00
9	2.25	39	9.75	69	17.25
10	2.50	40	10.00	70	17.50
11	2.75	41	10.25	71	17.75
12	3.00	42	10.50	72	18.00
13	3.25	43	10.75	73	18.25
14	3.50	44	11.00	74	18.50
15	3.75	45	11.25	75	18.75
16	4.00	46	11.50	76	19.00
17	4.25	47	11.75	77	19.25
18	4.50	48	12.00	78	19.50
19	4.75	49	12.25	79	19.75
20	5.00	50	12.50	80	20.00
21	5.25	51	12.75	81	20.25
22	5.50	52	13.00	82	20.50
23	5.75	53	13.25	83	20.75
24	6.00	54	13.50	84	21.00
25	6.25	55	13.75	85	21.25
26	6.50	56	14.00	86	21.50
27	6.75	57	14.25	87	21.75
28	7.00	58	14.50	88	22.00
29	7.25	59	14.75	89	22.25
30	7.50	60	15.00	90	22.50

Figure C-8

Temperature Versus Millivolts (MV)

Millivolts	Temperature	Millivolts	Temperature
3.00	700	10.75	2010
3.25	750	11.00	2050
3.50	800	11.25	2090
3.75	845	11.50	2130
4.00	890	11.75	2165
4.25	935	12.00	2200
4.50	980	12.25	2240
4.75	1030	12.50	2280
5.00	1070	12.75	2315
5.25	1120	13.00	2350
5.50	1160	13.25	2390
5.75	1200	13.50	2430
6.00	1245	13.75	2460
6.25	1290	14.00	2500
6.50	1330	14.25	2535
6.75	1375	14.50	2590
7.00	1420	14.75	2615
7.25	1460	15.00	2650
7.50	1500	15.25	2690
7.75	1540	15.50	2725
8.00	1580	15.75	2765
8.25	1620	16.00	2800
8.50	1660	16.25	2840
8.75	1700	16.50	2880
9.00	1740	16.75	2915
9.25	1780	17.00	2955
9.50	1820	17.25	2990
9.75	1860	17.50	3030
10.00	1900	17.75	3075
10.25	1935	18.00	3110
10.50	1975		

Velocity Pressure Traverse

Instrument check:

1. Flip excitation control switch (F) "On."
2. Turn "Zero M.V. Control" to "Zero."
3. Set recorder input selector switch (A) to "PT" position.
4. Set "Span M.V. Control" (black outer knob) on five or ten, as required. (Red inner knob should be fully counterclockwise.)
5. With pressure transducer at static conditions (pressure leads disconnected at transducer), zero recorder with zero adjust control (C).
6. Press calibrate button (D). Adjust "Calibrate Control" (B) until recorder scale reads as follows (dependent on transducer used and the M.V. span setting).

		Recorder Scale, %	
Transducer Ser. No.	M.V. Setting	5 M.V. Span	10 M.V. Span
11597	4.66	93.2	46.6
11598	4.51	90.2	45.1
11599	4.43	88.6	44.3
11600	4.56	91.2	45.6
11601	4.46	89.2	44.6
11602	4.53	90.6	45.3
11647	4.42	88.4	44.2
11655	4.90	98.0	49.0
11656	4.94	98.8	49.4
11657	4.73	94.6	47.3
11658	4.79	95.8	47.9
11659	4.87	97.4	48.7
11660	4.88	97.6	48.8
11661	4.78	95.6	47.8
11662	5.12	--	51.2
11663	4.90	98.0	49.0

7. Release calibrate button (D) and repeat steps (5) and (6) until recorder scale % is obtained. (Setting is correct when pen sweeps from zero to required recorder scale %.)
8. Return recorder input selector switch (A) to "Short" position.
9. Lock "Zero Adjust" (C) and "Calibrate Control" (B).
10. The recorder is now calibrated to read pressure differential with 0.25 inch of water equivalent to 5 M.V. and 0.5 inch of water equivalent to 10 M.V.

Probe Check:

1. Wire brush pitot openings.
2. Blow out pitot leads with compressed air.

   Warning - Never apply compressed air to transducer. Diaphram is easily ruptured by small (greater than 1-1/2" W.G.) pressure differences.

Operation:

1. Move probe to first test point.
2. Turn chart drive on "Fast."
3. Mark starting time on both data sheet and on chart.
4. Set recorder input selector switch (A) to "PT" position for 15 seconds.
5. Return recorder input selector switch (A) to "Short" position.
6. Mark test point number on chart.
7. Move probe to next point and repeat item 4, 5, and 6 until traverse is completed.
8. Turn chart drive "Off."
9. Mark stop time on data sheet and on chart.
10. Mark span MV setting on data sheet.
11. Withdraw probe from furnace.
12. Disconnect the transducer hose leads from the transducer and probe.
13. Mark average recorder readings on data sheet.
14. Convert recorder readings to In. H_2O. (If recorder span is 5 MV, go to Figure C-9; if recorder span is 10 MV, go to Figure C-10.)

    Enter velocity pressure, inches H_2O, on data sheet.

Dust Traverse

Calculations:

A dust sample will be collected isokinetically (based on the average velocity measured) from each of the six test points. In order to do this, certain calculations must be made.

1. Turn to Figure C-11.
2. Obtain correction factor corresponding to each test point temperature and enter it in column (1).
3. With test point temperature and velocity pressure, obtain nozzle CFM from sampling rate tables. Enter value in column (2).
4. Multiply column (1) by column (2) and enter flue gas CFM in column (3).
5. Add flue gas CFM (3) to seal air CFM (4) to obtain sample total CFM.
6. Turn to Figure C-12, Aerotec Cyclone Calibration Curve. Obtain ΔP, inches H_2O, corresponding to the sampler total CFM.

Probe check:

1. Wire brush dust sampling nozzle.
2. Be sure that nozzle and air slot are clear of obstruction.
3. Blowback dust tube. (Procedure: (1) close the ball valve ahead of the sample, (2) turn the aspirator off, and (3) open air blowback valve.)

Figure C-9
Recorder Reading Versus Velocity Press.
Recorder Span 5 MV

Rec. Rdng. %	Vel. Press. In. H_2O	Rec. Rdng. %	Vel. Press. In. H_2O	Rec. Rdng. %	Vel. Press. In. H_2O
1	.0025	31	.0775	61	.1525
2	.0050	32	.0800	62	.1550
3	.0075	33	.0825	63	.1575
4	.0100	34	.0850	64	.1600
5	.0125	35	.0875	65	.1625
6	.0150	36	.0900	66	.1650
7	.0175	37	.0925	67	.1675
8	.0200	38	.0950	68	.1700
9	.0225	39	.0975	69	.1725
10	.0250	40	.1000	70	.1750
11	.0275	41	.1025	71	.1775
12	.0300	42	.1050	72	.1800
13	.0325	43	.1075	73	.1825
14	.0350	44	.1100	74	.1850
15	.0375	45	.1125	75	.1875
16	.0400	46	.1150	76	.1900
17	.0425	47	.1175	77	.1925
18	.0450	48	.1200	78	.1950
19	.0475	49	.1225	79	.1975
20	.0500	50	.1250	80	.2000
21	.0525	51	.1275	81	.2025
22	.0550	52	.1300	82	.2050
23	.0575	53	.1325	83	.2075
24	.0600	54	.1350	84	.2100
25	.0625	55	.1375	85	.2125
26	.0650	56	.1400	86	.2150
27	.0675	57	.1425	87	.2175
28	.0700	58	.1450	88	.2200
29	.0725	59	.1475	89	.2225
30	.0750	60	.1500	90	.2250

Figure C-10
Recorder Reading Versus Velocity Press.
Recorder Span 10 MV

Rec. Rdng. %	Vel. Press. In. H_2O	Rec. Rdng. %	Vel. Press. In. H_2O	Rec. Rdng. %	Vel. Press. In. H_2O
1	.0050	35	.1750	68	.3400
2	.0100	36	.1800	69	.3450
3	.0150	37	1850	70	.3500
4	.0200	38	.1900	71	.3550
5	.0250	39	.1950	72	.3600
6	.0300	40	.2000	73	.3650
7	.0350	41	.2050	74	.3700
8	.0400	42	.2100	75	.3750
9	.0450	43	.2150	76	.3800
10	.0500	44	.2200	77	.3850
11	.0550	45	.2250	78	.3900
12	.0600	46	.2300	79	.3950
13	.0650	47	.2350	80	.4000
14	.0700	48	.2400	81	.4050
15	.0750	49	.2450	82	.4100
16	.0800	50	.2500	83	.4150
17	.0850	51	.2550	84	.4200
18	.0900	52	.2600	85	.4250
19	.0950	53	.2650	86	.4300
20	.1000	54	.2700	87	.4350
21	.1050	55	.2750	88	.4400
22	.1100	56	.2800	89	.4450
23	.1150	57	.2850	90	.4500
24	.1200	58	.2900	91	.4550
25	.1250	59	.2950	92	.4600
26	.1300	60	.3000	93	.4650
27	.1350	61	.3050	94	.4700
28	.1400	62	.3100	95	.4750
29	.1450	63	.3150	96	.4800
30	.1500	64	.3200	97	.4850
31	.1550	65	.3250	98	.4900
32	.1600	66	.3300	99	.4950
33	.1650	67	.3350	100	.5000
34	.1700				

Figure C-11
Temperature Correction Factor for Dust Sampling

Temperature	Correction Factor	Temperature	Correction Factor
1200	.345	2050	.225
1245	.336	2090	.222
1290	.328	2130	.220
1330	.321	2165	.217
1375	.313	2200	.215
1420	.305	2240	.212
1460	.299	2280	.209
1500	.292	2315	.207
1540	.285	2350	.204
1580	.280	2390	.202
1620	.274	2430	.199
1660	.268	2460	.197
1700	.265	2500	.195
1770	.261	2535	.192
1780	.256	2590	.189
1820	.251	2615	.187
1860	.247	2650	.185
1900	.243	2690	.183
1935	.240	2725	.181
1975	.236	2765	.178
2010	.233	2800	.176

Figure C-12
Aerotec Cyclone Calibration Curve

Total CFM	ΔP, In. H_2O	Total CFM	ΔP, In. H_2O
1.00	.8	3.05	6.5
1.05	.9	3.10	6.7
1.10	.9	3.15	6.9
1.15	1.0	3.20	7.2
1.20	1.1	3.25	7.4
1.25	1.1	3.30	7.7
1.30	1.2	3.35	7.9
1.35	1.3	3.40	8.2
1.40	1.4	3.45	8.4
1.45	1.5	3.50	8.7
1.50	1.6	3.55	8.9
1.55	1.7	3.60	9.2
1.60	1.8	3.65	9.5
1.65	1.9	3.70	9.7
1.70	2.0	3.75	10.0
1.75	2.1	3.80	10.3
1.80	2.2	3.85	10.6
1.85	2.4	3.90	10.9
1.90	2.5	3.95	11.1
1.95	2.6	4.00	11.4
2.00	2.7	4.05	11.7
2.05	2.9	4.10	11.9
2.10	3.0	4.15	12.2
2.15	3.1	4.20	12.5
2.20	3.3	4.25	12.9
2.25	3.5	4.30	13.0
2.30	3.7	4.35	13.4
2.35	3.9	4.40	13.8
2.40	4.0	4.45	14.1
2.45	4.1	4.50	14.4
2.50	4.3	4.55	14.8
2.55	4.5	4.60	15.1
2.60	4.7	4.65	15.5
2.65	4.9	4.70	15.8
2.70	5.1	4.75	16.2
2.75	5.2	4.80	16.5
2.80	5.4	4.85	17.0
2.85	5.6	4.90	17.4
2.90	5.8	4.95	17.7
2.95	6.0	5.00	18.0
3.00	6.2		

4. Set seal air flow to the dust nozzle at 2 CFM.
5. Zero water level in manometer and connect tubing between manometer and pitot tube lines.
6. Replace rubber washer in sample holder.
7. Mark label on empty sample jar with date, test number, probe, point, test station, and test observer.
8. Insert sample jar in sample holder and secure.

Operation:

1. Move probe to first test point.
2. Set required ΔP across the sampler by adjusting aspiration rate and start elapse timer.
3. Hold the ΔP value during entire sampling period by readjusting aspiration rate.
4. When blowback is needed, stop aspirator and elapse timer. Blowback for about 15 seconds. Reset aspirator to the ΔP and restart elapse timer.
5. Sample dust for 2-1/2 minutes of elapsed time.
6. Stop aspirator and remove the sample bottle, being sure not to lose any dust.
7. Cap the bottle and double check the marking for test number, point number, and test date.
8. Record elapsed sampling time and clock time on the data sheet and on the sample bottle.
9. Collect and carry dust samples to chemical laboratory when dust traverse is completed.

Temperature, Velocity, Dust, SO_2 and O_2 Sampling at Station 8

Equipment Required:

1. Nozzle
2. Sample probe
3. Aspirator
4. Cyclone separator
5. Pitot tube
6. O_2 analyzer
7. SO_2 analyzer
8. Potentiometer - thermocouple tables
9. Asbestos gloves
10. Draft gauge (inclined manometer)
11. C clamp
12. Rubber tubing
13. Red gauge oil

Sampling location - At boiler outlet at approximately elevation 375' 8", unit 10.

Sampling Procedure - Dust

Layout of Plane C-C is shown in Figure 24. For dust sampling, probes were inserted at 6 locations along the boiler outlet duct and aspiration rates were set according to calculated values determined from temperature and velocity pressure measurements. Each sample was obtained during a 15-minute sampling period.

Sample Identification

Each dust sample jar was identified immediately after collection as follows:

BOFA - Test number - probe number - point number - test date

(Example) BOFA - 1 - Pt8 - Pt8A - February 16, 1971

Where BOFA = Boiler outlet Fly Ash
1 = Test number
Pt8 = Test point 8
Pt8A = Test point 8; probe A
February 16, 1971 = Test date

Sample weighing and storage

Immediately after being properly identified, the samples were carried to the laboratory to be weighed; then distributed for further analysis.

Sampling Procedure - SO_2 and O_2

Six, fixed position probes inserted into the boiler outlet duct at Plane C-C were joined to provide a common sample from the east side and another common sample from the west side. Each sample line was connected to a Dupont 400 ultra-violet SO_2 analyzer to provide a continuous readout of SO_2 level. Daily, each analyzer was checked against standard calibration gas having an SO_2 content near that of real flue gas. Carborundum filters at the inlet lines were back blown daily to remove dust. Hand marking of time and events was done on the stripcharts which served as source material for calculation of SO_2 removal rates.

Oxygen measurements could also be taken through the SO_2 sampling system but were usually taken via probes inserted into dust probe ports. Probes could be connected to provide an average of 3 samples per side or to give individual traverses, as desired. A vacuum pump drew the sample through a drying column and a Beckman polarographic O_2 analyzer.

4. Analytical Procedures - Field Laboratory

This section contains only those procedures used at Shawnee and excludes standard methods for coal analyses used at the Central Laboratory.

Procedure	Analysis
1.	Calcium oxide in fly ash-lime mixture
2.	Magnesium oxide in fly ash-lime mixture
3.	Total sulfur in fly ash-limestone mixture and in coal by high temperature combustion
4.	Density determination of fly ash-lime mixture or limestone
5.	Average particle size and specific surface of ground limestone
6.	Hydration test to determine the degree of overburn of CaO in fly ash-lime mixture
7.	Precision of routine field laboratory analytical techniques

1. CALCIUM OXIDE IN FLY ASH-LIME MIXTURE

The following procedure is a modification of the accepted EDTA titration for calcium oxide in lime and limestone.

1. Weigh out 0.2000 ± 0.0002 g of fly ash-limestone mixture into 300 ml Erlenmeyer flask.
2. Add 10 ml of dilute hydrochloric acid (1 volume water + 1 volume hydrochloric acid).
3. Boil for one minute (cover with small watch glass to minimize losses).
4. Dilute to 100 ml with deionized or distilled water.
5. Add 5 ml of 1:1 triethanolamine and 5 ml concentrated ammonium hydroxide, stirring after each addition.
6. Adjust pH to 12-13, using 20% potasium hydroxide solution. (If no pH meter is available, add 20 ml of 20% potassium hydroxide solution.)
7. Add 40 mg Calcein indicator.
8. Titrate rapidly with 0.1 M EDTA solution to a purple end point, using a black background and diffused daylight
9. Calculate

$$\frac{\text{ml} \times 0.0056 \times 100}{0.2} = \%\ \text{CaO}$$

Calcein Indicator - Grind together 0.2 g Calcein indicator, 0.12 g thymolphthalein, and 20 g potassium chloride in a porcelain mortar. Transfer to a bottle and keep capped.

2. MAGNESIUM OXIDE IN FLY ASH-LIME MIXTURE

The following procedure titrates total calcium oxide and magesium oxide. The magnesium oxide is obtained by difference.

1-4. Dissolve sample as described above.

5. Add 20 ml 1:1 triethanolamine and 25 ml concentrated ammonium hydroxide, stirring after each addition.
6. Check pH. Add 20% potassium hydroxide to bring pH to 10 if necessary.
7. Add 40 mg of Phthalein Purple.
8. Titrate rapidly with 0.1 M EDTA solution to a colorless end point, using a white background.
9. Calculate

$$\frac{\text{ml (II)} - \text{ml (I)} \times 0.0040 \times 100}{0.2} = \%\ \text{MgO}$$

Phthalein Purple Indicator - Grind together 0.1 g phthalein purple indicator, 0.005 g methyl red, 0.05 g naphthol green, and 10 g potassium chloride in a porcelain mortar. Transfer to a bottle and keep capped. It is convenient to use a calibrated scoop for measuring the 40 mg of indicators.

3. TOTAL SULFUR IN FLY ASH-LIMESTONE MIXTURE AND IN COAL BY HIGH TEMPERATURE COMBUSTION

Summary—The sample is burned in a stream of oxygen. Approximately 95% of the sulfur is converted to sulfur dioxide, and a furnace factor is used to obtain accurate results. The furnace factor is obtained by analyzing a sample of known sulfur content and calculating the recovery percentage. The combustion gases are passed into a titrator containing an acid solution of potassium iodide and starch. A small amount of potassium iodate is added and a blue color develops.

$$KIO_3 + 5KI + 6HC1 = 6KC1 + 3I_2$$

$$I_2 + \text{starch} = \text{starch iodide blue}$$

As sulfur is released, it bleaches the blue color by converting the I_2 to HI

$$SO_2 + I_2 + 2H_2O = H_2SO_4 + 2HI$$

and more iodate solution is added to maintain the blue coloration. The amount of standard iodate consumed during the combustion is a measure of the sulfur content of the sample.

Apparatus

A high temperature furnace made by LECO* and shown in Figure C-13 was used for rapid sulfur determinations. Figure C-14 shows the automatic sulfur titrator and Figure C-15 the LECO purifying train.

Procedure

Solutions

Potassium Iodate-Iodine Solution (1 ml KIO_3 = 0.5 mg S.)—Dissolve 1.11 g KIO_3 and 5 g KI in distilled water and dilute to exactly 1 liter. (It is desirable to dissolve 6-8 pellets of KOH in the water before adding KIO_3 and KI.)

Starch Solution—Make a suspension by adding 2 g Arrowroot starch to 50 ml distilled water. Add this mixture, with stirring, to 150 ml of boiling distilled water. Allow to boil for 2 minutes. Cool to room temperature and add 6 g KI.

A single determination requires about 7 minutes.

*Laboratory Equipment Company

FIGURE C-13

LECO FURNACE

MODEL 521-500

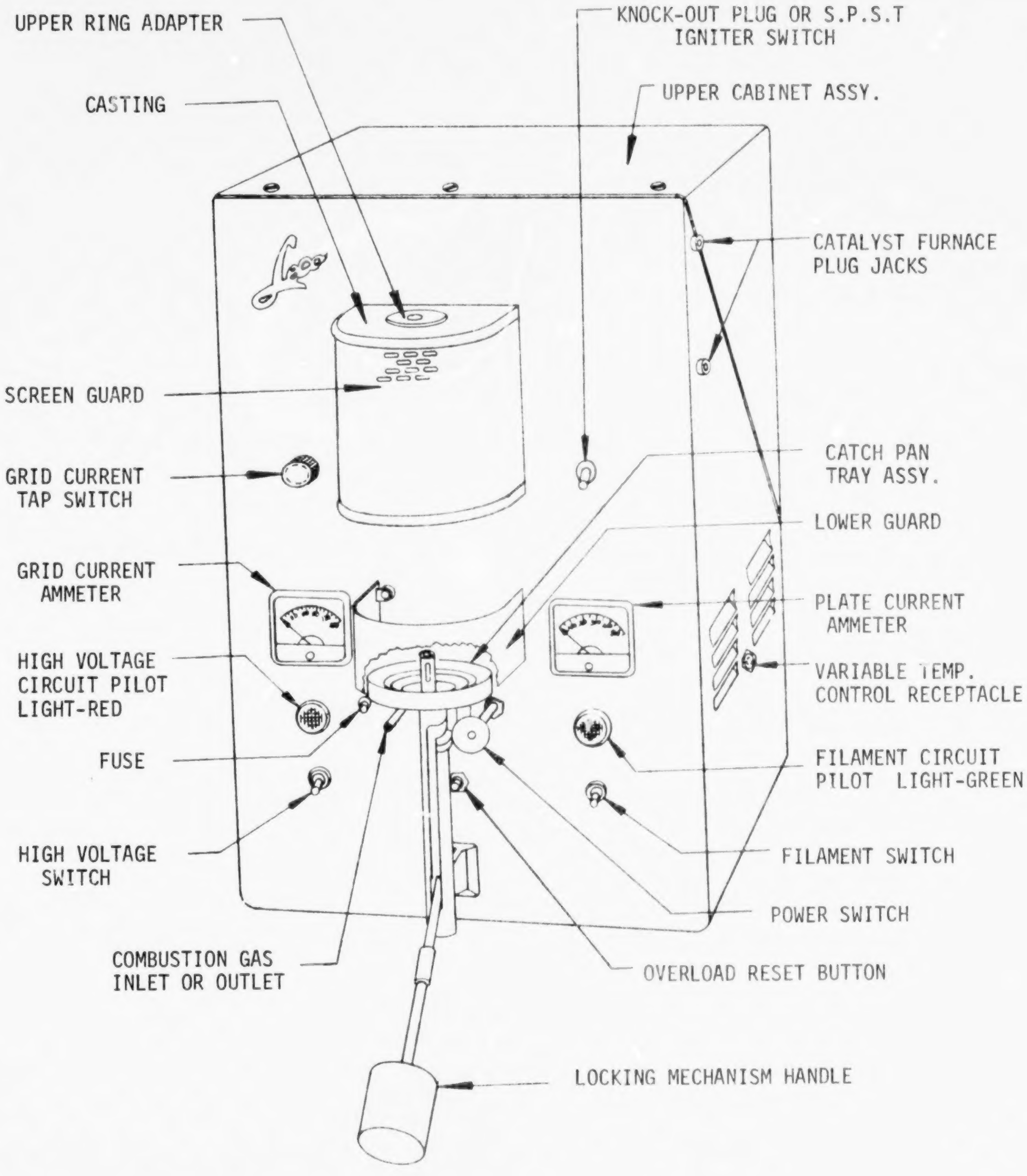
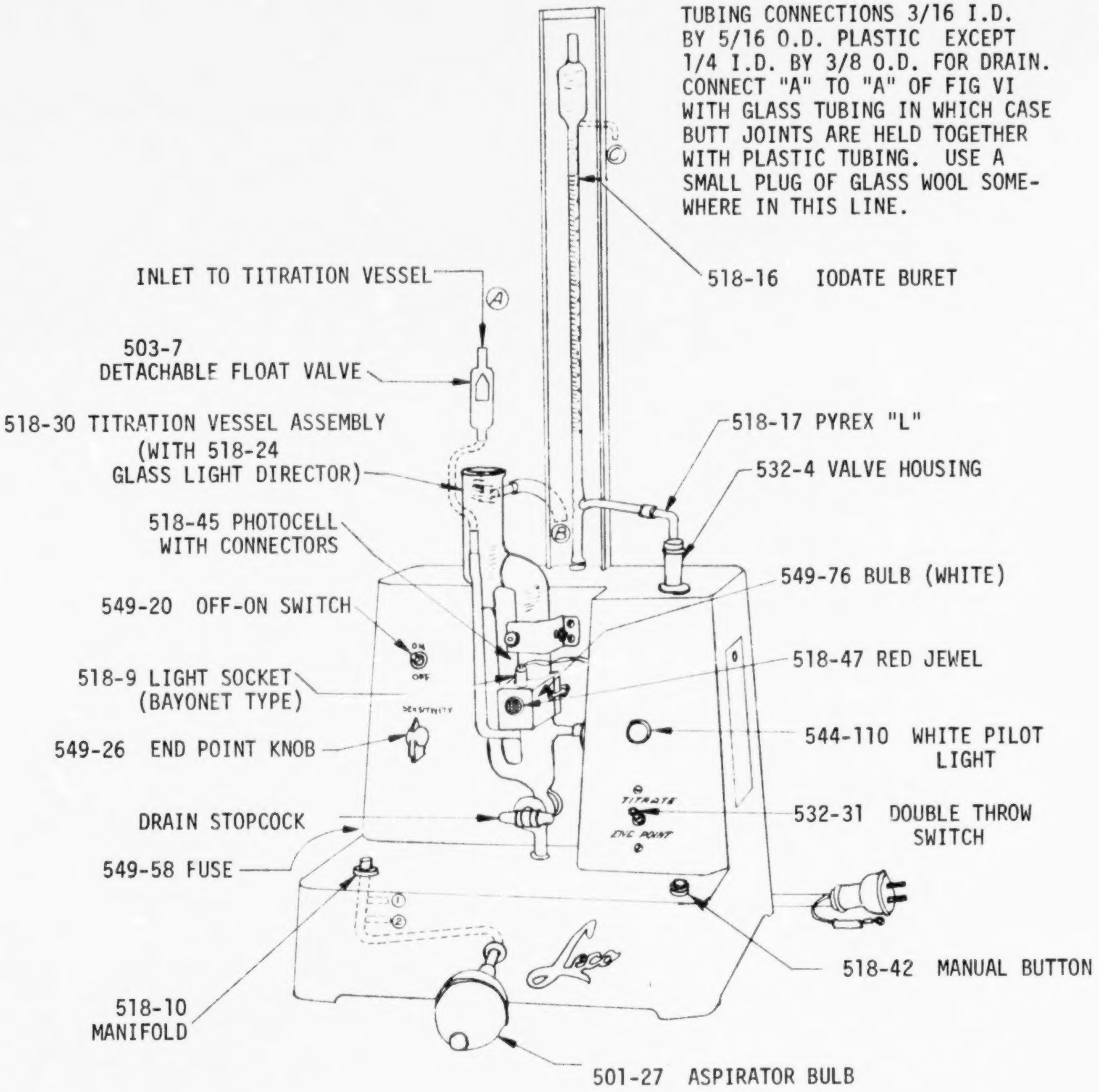


FIGURE C-14

AUTOMATIC SULFUR TITRATOR

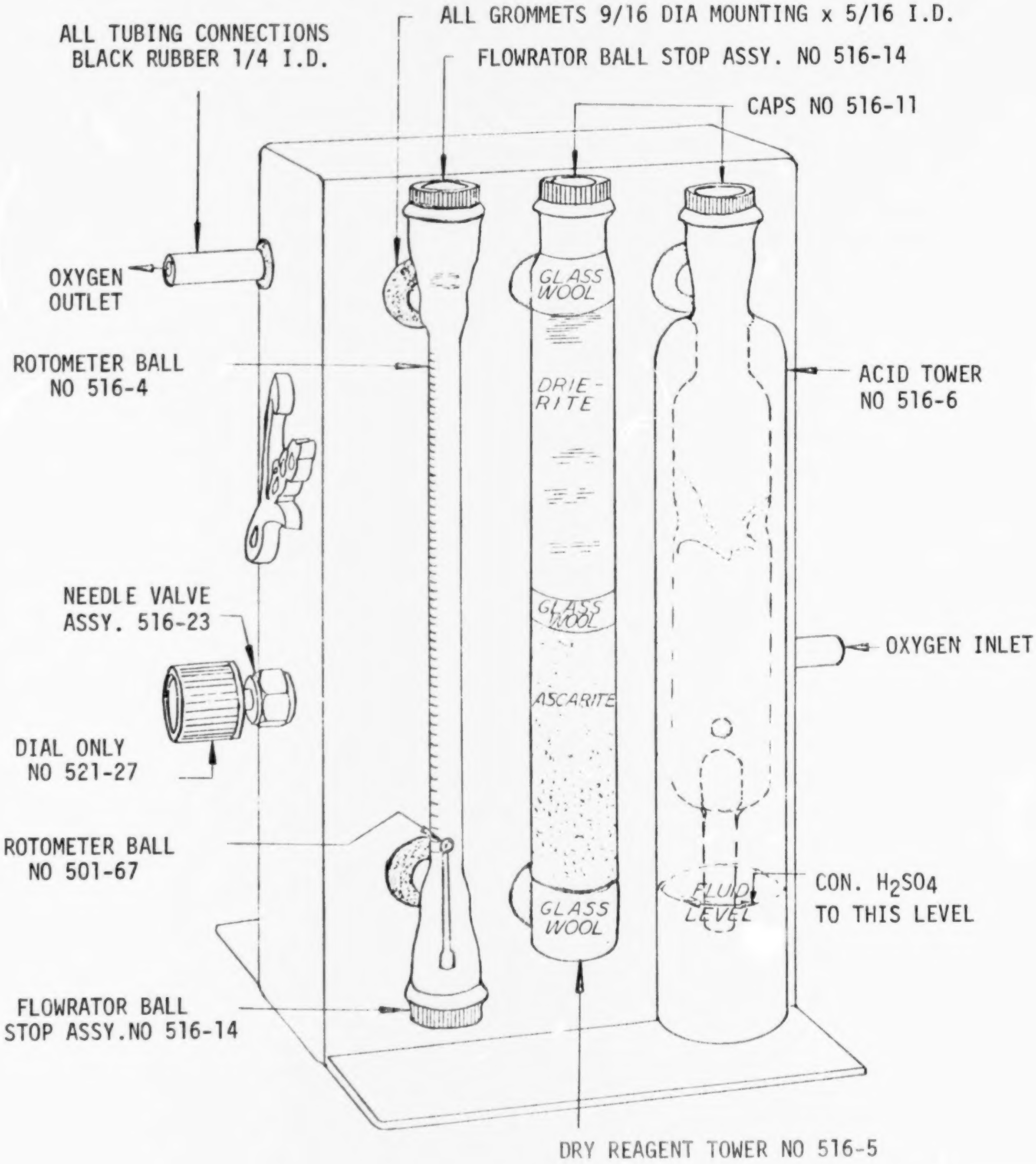
MODEL 532



TUBING CONNECTIONS 3/16 I.D. BY 5/16 O.D. PLASTIC EXCEPT 1/4 I.D. BY 3/8 O.D. FOR DRAIN. CONNECT "A" TO "A" OF FIG VI WITH GLASS TUBING IN WHICH CASE BUTT JOINTS ARE HELD TOGETHER WITH PLASTIC TUBING. USE A SMALL PLUG OF GLASS WOOL SOMEWHERE IN THIS LINE.

LECO PURIFYING TRAIN

MODEL 516



ALL GROMMETS 9/16 DIA MOUNTING x 5/16 I.D.
ALL TUBING CONNECTIONS BLACK RUBBER 1/4 I.D.
FLOWRATOR BALL STOP ASSY. NO 516-14
CAPS NO 516-11
OXYGEN OUTLET
GLASS WOOL
ROTOMETER BALL NO 516-4
DRIE-RITE
ACID TOWER NO 516-6
NEEDLE VALVE ASSY. 516-23
GLASS WOOL
OXYGEN INLET
ASCARITE
DIAL ONLY NO 521-27
ROTOMETER BALL NO 501-67
CON. H_2SO_4 TO THIS LEVEL
FLUID LEVEL
GLASS WOOL
FLOWRATOR BALL STOP ASSY.NO 516-14
DRY REAGENT TOWER NO 516-5

4. DETERMINATION OF DENSITY OF FLY ASH-LIME OR LIMESTONE

This analysis is a prerequisite for determing average particle size by means of the Fisher Sub-Sieve Sizer. Since there is a hydratable fraction in the fly ash-lime mix, no water can be used.

For the following procedure, only a 50-ml volumetric flask, a 50 ml burette, an analytical balance, and mineral spirits are required.

Procedure

1. Weigh a clean, dry 50-ml volumetric flask.
2. Put 5 to 10 grams of sample into flask and reweigh.
3. Fill flask to volume with mineral spirits, from 50-ml burette.
4. Sample weight divided by 50-titration gives sample density.

Time required per analysis about 10 minutes.

5. AVERAGE PARTICLE SIZE AND SPECIFIC SURFACE OF GROUND LIMESTONE

Fisher Sub-Sieve Sizer—The Sub-Sieve Sizer operates on the air-permeability principle for measuring the average particle size of powders. The principle finds its basis in the fact that a current of air flows more readily through a bed of coarse powder than through an otherwise equal bed of fine powder.

Preliminary Data—Before average particle size can be determined, it is necessary to know the true density of the material and the optimum porosity point. Optimum porosity point is obtained by following the instructions in the Fisher Instruction Manual. True density is obtained by displacement in light oil.

Calibration—Calibration may be effected by either of two means. Daily calibration should be made by using the Fisher Sub-Sieve Sizer Calibrator. This is a secondary standard consisting of a synthetic ruby orifice mounted in a tube similar to a sample tube. The calibrator is used as described in the attached sheet under Catalog No. 14-311V2.

Periodically, the Sub-Sieve Sizer should be calibrated against National Bureau of Standards' Sample No. 114, a powdered Portland Cement of certified specific surface. This calibration is described in the Fisher Instruction Manual.

Measuring Particle Size—Follow instructions as outlined in the Fisher Instruction Manual.

Calculations—No calculation is necessary for average particle size. The value is read directly off the Calculator Chart.

To obtain specific surface, substitute in the following equation:

$$S_w = \frac{6 \times 10^4}{p d_m}$$

in which

S_w = specific surface in cm^2/gram
p = true density
d_m = average particle diameter in microns

6. HYDRATION TEST TO DETERMINE THE DEGREE OF OVERBURN OF CaO IN FLY ASH-LIME MIXTURE

1. Weigh 1 gram of the fly ash-lime mix into a tared 3A crucible and record net weight.
2. Ignite sample at 1,300° F. in muffle furnace with a little aspiration for one hour. Desiccate until cool and reweigh. Record weight.
3. Pipet 5 ml of water into the crucible, let stand for 1/2 hour.
4. Evaporate water, from the crucible, under an infra-red lamp (approximately 15 minutes at 250 watt setting).
5. Place crucible in drying oven for 1 hour oven temperature should be 260° C.
6. Remove from oven and desiccate; reweigh the dish and its contents. Record weight gain.

Calculation:

$$\% \text{ CaO (Free)} = \% \text{ CaO (in sample)} - \%\text{SO}_2 \text{ (in sample)} \times \frac{56}{64}^{*}$$

$$\% \text{ wt gain of CaO} = \frac{\text{Weight gain of Sample}}{\frac{\% \text{ CaO (Free)}}{100} \times \text{Sample weight}} \times 100$$

*Molecular weights of $\frac{CaO}{SO_2}$

Hydrochloric Acid Solution—Measure 30 ml of concentrated acid and add to 1,970 ml of distilled water.

LECO Furnace Operation

Turn on filament switch and high voltage switch and allow to warm up for 45 seconds.

Titrator Operation

With the oxygen flow set at 1 1/min add hydrochloric acid solution to the middle of the bell shaped portion of the titration vessel. Add the starch solution directly to the titration vessel. Always fill to the same point. Turn on the power switch 549-20 and allow the instrument to warm up with the 532-31 double throw switch in neutral (center) position. Turn the end point control 549-26 to the extreme left. Turn the double throw to end point (down) position, and slowly rotate the end point control in a clockwise direction until it has added KIO_3 in the amount to give a solid medium blue color. Leave the end point control in this position. Refill the KIO_3 buret. About three buret divisions give the proper color if the starch is properly prepared. Place switch in titrate position.

Sample Loading

Weight *0.2500 ± 0.0002 grams fly ash-limestone mixture and transfer to a Leco crucible. Add two level scoops of low sulfur iron powder and one scoop of granular tin. Do not mix these with sample. Cover crucible with porous cover and place on furnace pedestal. Raise and lock sample into position. At completion of combustion period, read buret and remove sample crucible. Drain and refull titration vessel and refill KIO_3 buret.

Calculation

$$\% \text{ Sulfur in sample} = \frac{\text{buret reading} \times 2.5}{(\text{F})\ (\text{sample weight})}$$

The furance factor (F) is determined by analyzing a sample of known sulfur content. It will be between 0.92 and 0.97.

The sample weight may be varied if sulfur is too high to titrate with the KIO_3 solution.

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*For coal analysis this sample loading becomes "Weigh 0.0500 to 0.0725 ± 0.0002 grams."

7. PRECISION OF ANALYTICAL TECHNIQUES

Fisher Avg. Particle Size, μ	CaO in Lime-Fly Ash Mixture, %
5.10	41.81
5.05	41.37
5.00	41.73
5.02	42.29
5.02	42.00
5.02	42.12
4.98	42.21
5.00	41.30
5.15	42.17
5.00	42.52
$\bar{x}$ = 5.03	$\bar{x}$ = 41.95
σ = ±0.05	σ = ±0.35

Sulfur in Coal 2% Level	Sulfur in Coal 4% Level	SO$_4$ in Lime-Fly Ash, % (As SO$_2$)
2.13	4.11	3.84
2.17	4.08	3.62
2.07	4.11	3.78
1.90	4.00	3.54
2.02	4.24	3.72
1.93	4.09	3.51
1.99	4.14	3.51
2.10	4.24	3.69
2.07	4.16	3.72
2.08	4.07	3.73
$\bar{x}$ = 2.05	$\bar{x}$ = 4.12	$\bar{x}$ = 3.67
σ = ±0.09	σ = ±0.08	σ = ±0.11

SHAWNEE UNIT 10
SAMPLING STATIONS

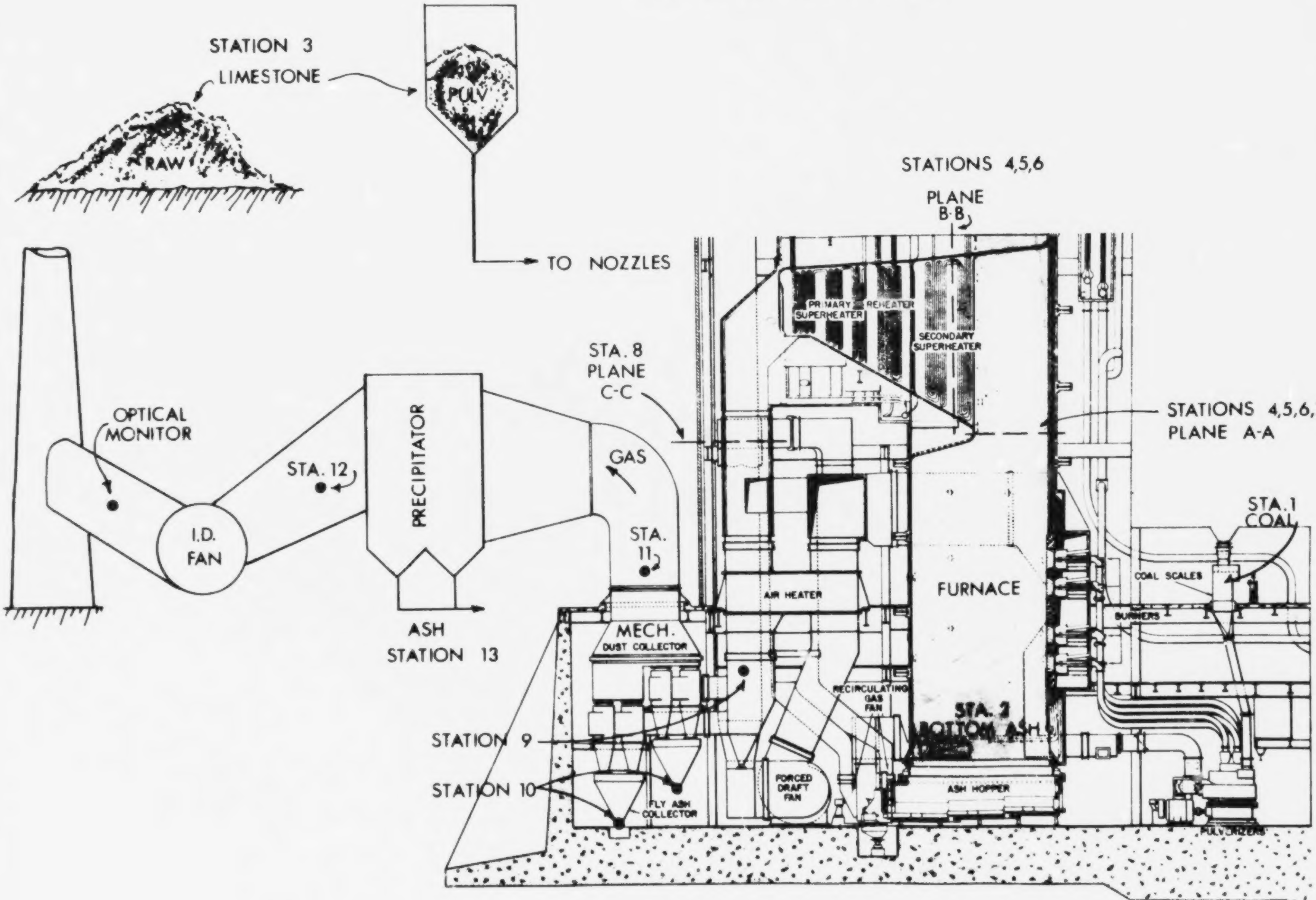

FIGURE 11

APPENDIX D

Computer Printouts for Phase I Tests

APPENDIX D

Table I-1

Summary of Phase I Tests

Test No.	Injection Location	Stoich.	Plant Composite S in Coal, %	Injection Velocity, Ft./Sec.	Load MW	Excess Air, %		Initial SO_2 Level, ppm		Injection Angle	Particle Size No.	Limestone Utilization, %		Limestone Distribution Index*		SO_2 Removal, %	
						E	W	E	W			E	W	E	W	E	W
1	Lower Rear	1.86	2.4	130	140	26.5	24.3	1840	1840	0	4.0	11.3	11.7	5.4	6.5	15.1	10.8
2	Upper Rear	1.55	2.6	132	140	35.5	33.3	1600	1640	0	4.0	11.4	15.1	11.0	13.5	23.0	20.1
3	Upper Rear	1.84	2.2	59	143	27.3	20.0	1880	1880	0	4.5	6.8	7.7	16.6	14.1	15.2	7.3
4	Upper Rear	3.10	1.6	127	144	25.0	20.0	1190	1190	0	4.4	9.4	10.1	14.2	11.8	14.8	14.8
5	Upper Rear	3.68	1.4	67	142	18.0	16.7	1240	1240	0	4.2	7.2	6.3	18.2	16.3	14.8	14.8
6	Lower Rear	2.11	1.8	68	142	21.7	23.9	1480	1540	0	4.2	6.2	6.6	10.2	11.8	11.4	10.3
7	Lower Rear	2.30	2.0	130	140	18.3	19.2	2040	2120	0	4.6	5.2	6.5	11.0	8.8	11.0	9.4
8	Lower Rear	2.43	2.1	68	140	23.5	20.0	1900	1840	0	4.5	7.3	5.7	11.8	11.9	12.0	10.9
9	Upper Rear	1.47	2.5	940	140	14.1	18.0	2240	2160	0	4.7	10.4	9.0	15.0	12.7	13.2	14.2
10R2	Upper Rear	1.33	3.8	940	139	35.5	32.9	2400	2480	0	5.0	9.4	10.0	12.6	12.3	13.1	11.0
11	Front	1.53	3.3	195	139	29.6	31.3	2400	2440	0	5.0	7.9	8.6	14.2	12.7	4.7	11.0
12R3	Front	1.11	3.6	198	139	37.7	35.0	2360	2400	0	5.0	15.1	13.9	12.9	15.2	6.1	12.4
13	Front	1.76	2.2	101	142	37.7	37.7	1600	1600	0	4.7	7.1	9.1	17.7	15.8	14.1	12.9
14	Front	1.46	3.3	192	144	37.7	37.7	1800	1800	0	4.6	5.9	7.2	14.7	16.1	16.8	16.8
15	Upper Rear	1.75	2.1	945	142	40.0	33.3	1600	1520	0	4.8	9.9	12.8	11.8	14.1	27.3	26.2
16	Upper Rear	1.50	3.2	940	142	29.6	31.3	2680	2680	0	4.7	20.1	16.5	14.2	12.3	15.3	13.7
17	Upper Rear	1.01	3.5	131	142	29.6	31.3	2520	2400	+45	4.8	14.5	13.0	19.9	15.9	8.1	16.0
18	Upper Rear	1.77	2.4	131	141	29.6	37.3	2680	2480	+45	4.7	11.9	13.7	18.6	20.9	11.0	17.2
19	Upper Rear	1.16	3.0	132	142	38.2	39.1	2200	2200	-45	4.7	11.1	12.5	12.3	10.0	13.3	11.9
20	Upper Rear	1.69	3.0	132	142	38.2	39.1	2400	2160	-45	4.7	9.0	9.0	11.9	10.4	14.3	14.2
21	Upper Rear	0.87	2.6	134	138	16.0	16.6	2200	2080	-45	5.1	7.2	10.1	10.3	7.5	8.2	6.5
22	Upper Rear	1.76	1.7	131	140	25.0	15.4	1600	1680	0	4.8	11.8	11.1	18.0	13.6	17.3	15.0
23	Upper Rear	1.07	3.7	68	140	33.8	28.8	2720	2760	0	4.4	11.0	12.5	18.7	15.0	9.4	5.8
24	Upper Rear	1.70	3.2	67	139	32.9	39.1	2480	2480	-45	4.6	5.6	7.6	13.2	11.0	6.7	4.7
25	Upper Rear	1.29	4.0	68	116	22.1	23.5	3000	2920	0	5.2	6.7	5.1	13.2	11.8	8.7	8.9
26	Upper Rear	1.29	4.2	131	118	30.4	30.4	3200	3200	-45	4.8	7.9	8.7	12.3	10.3	4.3	5.7
27	Upper Rear	1.10	2.3	69	120	11.9	11.0	1960	2000	-45	5.7	10.2	11.3	8.1	8.1	8.7	11.5
28	Upper Rear	1.13	2.5	135	117	26.5	28.2	1800	1900	0	5.7	12.5	13.8	12.0	11.2	11.1	11.9
6A	Lower Rear	1.19	2.6	69	137	22.8	23.5	2400	2360	0	4.4	9.5	8.6	13.4	16.7	6.9	4.3
7A	Lower Rear	1.72	2.3	132	139	17.3	21.6	2080	1960	0	4.8	6.9	6.1	4.9	9.6	11.2	10.9
8A	Lower Rear	2.01	2.4	68	140	22.1	23.5	2080	2000	0	4.5	6.5	7.4	7.0	11.5	11.2	10.8
2A	Upper Rear	1.11	2.1	133	138	35.5	32.1	1620	1520	0	5.1	10.3	12.2	13.7	13.4	11.3	17.1
4A	Upper Rear	1.39	1.9	132	139	27.3	20.7	1760	1660	0	4.3	6.9	8.0	13.0	15.4	14.2	21.7
29	Upper Rear	0.86	1.7	136	78	27.0	28.0	1560	1440	0	5.0	12.3	17.0	9.0	8.5	13.0	14.5
1A	Lower Rear	1.44	2.7	130	138	25.4	29.2	2440	2480	0	5.1	7.4	6.1	4.1	11.4	10.9	8.6

*See Appendix E

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          TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

               SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

            FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.1       DATE:          MAY 12, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                  140
   BOILER LOAD, MLBS/HR                           985
   COAL RATE, LBS/HR                           122039.
   LIMESTONE RATE, LBS/LBCOAL                    0.147
   INJECTION VELOCITY, FT/SEC                     130
   INJECTION ANGLE,DEGREES                          0
   INJECTION ELEVATION                         LOWER REAR
   LIMESTONE TYPE, BCR NO.                       2061
   PARTICLE SIZE, MICRONS                         4.0
   STOICHIOMETRY                                 1.86
   COAL TYPE,CONTRACT NO.                       43T15
   EXCESS AIR,PERCENT -      WEST    24.3    EAST   26.5

COAL ANALYSIS - PROXIMATE       ACTUAL

            VOLATILE    FIXED
  MOISTURE   MATTER    CARBON       ASH       SULFUR
     13.0     31.1       44.3      11.6         2.4

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
     4.06      1.21      6..83       2.40      11.60      13.00


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  11.7 EAST  11.3


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                  METHOD 1      METHOD 2      METHOD 3
                WEST  EAST    WEST  EAST    WEST  EAST
                12.2  17.6    13.8  14.1    10.7  15.0


SO2 MATERIALS BALANCE         INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                  5858.           6640.             782.

CAO MATERIALS BALANCE            10052.           6238.           -3814.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE           41.52

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  4.71   EAST  4.64
```

```
TEST NO.  1     DATE:           MAY 12, 1970  INPUT DATA

 1             MAY 12, 1970  ACTUAL  1  1 0.00294    1.00    0.41

  130  985 4.0 2061   0                LOWER REAR       43T15   140

  13.0  31.1  44.3  11.6   2.4

   C. RATE    STD   S BA    L/C   C  BA C MECH C ELEC S MECH S ELEC
 122039.    1.86   0.83   0.15  14.51  45.92  13.63   2.62   2.42

         EXA    T BO    S FA    C FA     SOB     SOD     SOA DELS B DELS E
WEST    24.3    715.    4.55   33.94   1840.   1560.   1720.   140.    240.
EAST    26.5    728.    4.56   35.29   1840.   1520.   1760.   220.    320.

     24  TEST POINTS,SAMPLING PLANE A-A,WEST SIDE

       MV          VP        STAT      T SAMP       DUST       CAO         SO2    SO2 PPM
     11.50        0.21      -6.00      160.00       0.51      61.54        0.63   1840.00
     11.30        0.24      -6.00      160.00       0.67      45.44        0.78   1840.00
      9.80        0.08      -6.00      160.00       0.09      46.13        1.23   1840.00
     12.00        0.13      -6.00      160.00       0.49      41.55        1.52   1840.00
      9.00        0.08      -6.00      160.00       0.44      45.61        1.54   1840.00
      8.30        0.12      -6.00      160.00       0.10      44.97        1.80   1840.00
     12.00        0.22      -6.00      160.00       0.56      54.18        0.76   1840.00
     13.00        0.23      -6.00      160.00       0.76      51.73        0.88   1840.00
     13.50        0.22      -6.00      160.00       0.59      55.85        1.33   1840.00
     13.50        0.23      -6.00      160.00       0.49      46.90        0.94   1840.00
     13.50        0.24      -6.00      160.00       0.21      57.30        1.07   1840.00
     12.50        0.17      -6.00      160.00       0.03      62.93        0.44   1840.00
     10.00        0.06      -6.00      160.00       0.35      48.43        2.16   1840.00
     11.50        0.05      -6.00      160.00       0.15      45.46        2.11   1840.00
     12.00        0.06      -6.00      160.00       0.29      49.48        1.75   1840.00
     12.00        0.09      -6.00      160.00       0.18      46.48        1.41   1840.00
     12.00        0.15      -6.00      160.00       0.50      49.93        1.22   1840.00
     11.50        0.09      -6.00      160.00       0.05      68.59        1.26   1840.00
      9.80        0.02      -6.00      160.00       0.61      49.25        1.32   1840.00
     11.00        0.05      -6.00      160.00       0.37      50.09        0.78   1840.00
     11.40        0.06      -6.00      160.00       0.61      49.37        0.95   1840.00
     11.50        0.10      -6.00      160.00       1.05      50.19        0.48   1840.00
     11.50        0.11      -6.00      160.00       0.40      54.69        0.63   1840.00
     11.00        0.10      -6.00      160.00       0.09      61.92        0.63   1840.00

     AVERAGE CAO IN DUST,%,SAMPLING PLANE                    51.58
```

```
TEST NO.  1     DATE:          MAY 12, 1970

24  TEST POINTS,SAMPLING PLANE A-A,EAST SIDE

   MV           VP        STAT     T SAMP       DUST       CAO        SO2    CO2 PPM
  9.50        0.07       -6.00     160.00       0.04      42.41       0.65   1840.00
  9.50        0.06       -6.00     160.00       0.44      55.73       0.81   1840.00
  9.50        0.07       -6.00     160.00       0.25      59.92       1.84   1840.00
  9.80        0.10       -6.00     160.00       0.31      54.42       0.68   1840.00
 10.00        0.12       -6.00     160.00       0.89      47.72       0.75   1840.00
  8.80        0.09       -6.00     160.00       1.17      47.92       0.88   1840.00
 11.50        0.11       -6.00     160.00       0.09      54.78       0.88   1840.00
 11.80        0.04       -6.00     160.00       0.27      54.77       0.87   1840.00
 12.00        0.15       -6.00     160.00       0.30      60.11       0.85   1840.00
 12.50        0.16       -6.00     160.00       0.12      50.35       0.60   1840.00
 12.50        0.17       -6.00     160.00       0.26      55.47       0.47   1840.00
 11.80        0.19       -6.00     160.00       0.59      48.81       1.32   1840.00
 11.00        0.11       -6.00     160.00       0.59      49.31       0.71   1840.00
 11.50        0.11       -6.00     160.00       0.21      53.67       0.85   1840.00
 11.30        0.14       -6.00     160.00       0.62      53.46       1.12   1840.00
 11.50        0.11       -6.00     160.00       0.17      48.18       1.03   1840.00
 11.50        0.08       -6.00     160.00       0.04      46.26       0.85   1840.00
 11.00        0.10       -6.00     160.00       0.58      40.93       1.33   1840.00
  9.30        0.05       -6.00     160.00       0.43      47.03       1.27   1840.00
  9.80        0.08       -6.00     160.00       0.54      48.81       1.18   1840.00
 10.00        0.06       -6.00     160.00       0.41      51.94       1.09   1840.00
 10.50        0.05       -6.00     160.00       0.28      44.52       0.82   1840.00
 10.80        0.06       -6.00     160.00       0.29      42.13       1.14   1840.00
 10.00        0.05       -6.00     160.00       0.43      42.11       1.26   1840.00

 AVERAGE CAO IN DUST,%,SAMPLING PLANE                    50.03
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TEST NO.  1      DATE:            MAY 12, 1970
   SAMPLING PLANE A-A,WEST SIDE

                        LIMESTONE DISTRIBUTION INDEX

   SAMPLING        SO2     CAO GR LDG  VELOCITY     SO2        CAO     THEORET CAO
   LOCATION        PPM     GRNS/CUFT    FT/SEC   CUFT/SEC   GRNS/SEC   GRNS/SEC

       1          1840.       2.15       67.1     0.0235       27.        23.
       2          1840.       1.94       71.3     0.0253       27.        25.
       3          1840.       0.44       39.3     0.0153        4.        15.
       4          1840.       1.80       53.6     0.0182       18.        18.
       5          1840.       2.06       38.2     0.0157       18.        16.
       6          1840.       0.37       45.6     0.0197        4.        20.
       7          1840.       2.06       69.7     0.0237       27.        24.
       8          1840.       2.68       73.2     0.0236       34.        24.
       9          1840.       2.33       72.6     0.0228       29.        23.
      10          1840.       1.59       74.2     0.0233       20.        23.
      11          1840.       0.81       75.8     0.0238       11.        24.
      12          1840.       0.15       62.1     0.0205        2.        21.
      13          1840.       2.07       34.2     0.0132       15.        13.
      14          1840.       0.96       32.7     0.0115        6.        11.
      15          1840.       1.87       36.4     0.0124       13.        12.
      16          1840.       0.89       44.6     0.0152        7.        15.
      17          1840.       2.05       57.5     0.0196       22.        20.
      18          1840.       0.36       43.9     0.0154        3.        15.
      19          1840.       6.33       19.6     0.0076       26.         8.
      20          1840.       2.56       32.3     0.0116       16.        12.
      21          1840.       3.85       35.8     0.0126       26.        13.
      22          1840.       5.23       46.3     0.0162       46.        16.
      23          1840.       2.07       48.6     0.0170       19.        17.
      24          1840.       0.55       45.6     0.0164        5.        16.

  AVERAGE CAO GR LDG,GRNS/CUFT =    1.97

      R = 0.230

      T = 0.848

      AVG. % OFF THEORETICAL      54

      SIGMA (% OFF)               58

                         SUM     112


      CHI-SQUARE (% OFF)        198

      SIGMA(% CAO IN DUST)        6.6

      AVG.STOICH.DEVIATION       56.80

FLY ASH LOADING,GRNS/CUFT,AT STANDARD CONDITIONS - - AVERAGE=  1.96
   1.34        2.33        0.51        2.53        2.45        0.45
   1.74        2.50        1.84        1.80        0.61        0.09
   2.21        1.15        1.91        1.02        2.06        0.16
   6.52        2.56        3.95        5.19        1.72        0.34
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TEST NO.  1      DATE:            MAY 12, 1970
   SAMPLING PLANE A-A,WEST SIDE

                         EFFECTIVE STOICHIOMETRY

SAMPLING     SO2       CAO      RATIO     STOICHIO SO2 RECOVERED  SO2 REMOVAL
LOCATION  CUFT/SEC GRNS/SEC CAO/SO2   QUAN.CAC FRACTION   CUFT    EFFICIENCY

    1      0.0235      27.    1169.     1.069     0.355   0.008          1.0
    2      0.0253      27.    1054.     0.964     0.327   0.008          1.4
    3      0.0153       4.     238.     0.217     0.085   0.001          0.5
    4      0.0182      18.     978.     0.894     0.307   0.006          2.9
    5      0.0157      18.    1117.     1.022     0.342   0.005          3.0
    6      0.0197       4.     199.     0.182     0.072   0.001          0.6
    7      0.0237      27.    1120.     1.024     0.343   0.008          1.3
    8      0.0236      34.    1459.     1.334     0.421   0.010          2.0
    9      0.0228      29.    1267.     1.158     0.378   0.009          2.4
   10      0.0233      20.     864.     0.790     0.277   0.006          1.4
   11      0.0238      11.     443.     0.405     0.153   0.004          0.7
   12      0.0205       2.      80.     0.074     0.030   0.001          0.0
   13      0.0132      15.    1127.     1.031     0.345   0.005          4.0
   14      0.0115       6.     520.     0.476     0.177   0.002          1.9
   15      0.0124      13.    1014.     0.927     0.316   0.004          2.9
   16      0.0152       7.     483.     0.442     0.166   0.003          1.2
   17      0.0196      22.    1116.     1.021     0.342   0.007          2.2
   18      0.0154       3.     195.     0.178     0.071   0.001          0.3
   19      0.0076      26.    3439.     3.145     0.725   0.006          7.4
   20      0.0116      16.    1394.     1.275     0.407   0.005          1.7
   21      0.0126      26.    2092.     1.913     0.544   0.007          3.2
   22      0.0162      46.    2844.     2.601     0.656   0.011          2.2
   23      0.0170      19.    1126.     1.029     0.344   0.006          1.0
   24      0.0164       5.     296.     0.271     0.105   0.002          0.2

EFFECTIVE STOICHIOMETRY = 0.934     AVERAGE POINT STOICHIOMETRY = 0.977

TEMPERATURES,DEGREES FAHRENHEIT                    AVERAGE =  2119.
 2126.       2096.       1867.       2201.       1742.      1631.
 2201.       2351.       2426.       2426.       2426.      2276.
 1897.       2126.       2201.       2201.       2201.      2126.
 1867.       2052.       2111.       2126.       2126.      2052.

DUST LOADING,GRNS/CUFT,AT STANDARD CONDITIONS
   3.49        4.27        0.95        4.33        4.51       0.82
   3.80        5.19        4.17        3.39        1.42       0.24
   4.28        2.11        3.77        1.91        4.11       0.52
  12.85        5.12        7.80       10.43        3.79       0.88

GAS VELOCITY,FT/SEC                                AVERAGE =   50.8
   67.1        71.3        39.3        53.6        38.2       45.6
   69.7        73.2        72.6        74.2        75.8       62.1
   34.2        32.7        36.4        44.6        57.5       43.9
   19.6        32.3        35.8        46.3        48.6       45.6

LIMESTONE UTILIZED,PERCENT
    0.9         1.5         2.3         3.2         3.0        3.5
    1.2         1.5         2.1         1.8         1.6        0.6
    3.9         4.1         3.1         2.7         2.1        1.6
    2.3         1.4         1.7         0.8         1.0        0.9
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TEST NO.  1     DATE:          MAY 12, 1970
   SAMPLING PLANE A-A,EAST SIDE

                     LIMESTONE DISTRIBUTION INDEX

 SAMPLING       SO2    CAO GR LOG VELOCITY    SO2       CAO    THEORET CAO
 LOCATION       PPM    GRNS/CUFT   FT/SEC  CUFT/SEC  GRNS/SEC  GRNS/SEC

     1         1840.      0.19      36.4    0.0144      1.        15.
     2         1840.      2.95      33.7    0.0134     21.        14.
     3         1840.      1.67      36.4    0.0144     13.        15.
     4         1840.      1.59      43.9    0.0171     15.        18.
     5         1840.      3.68      48.4    0.0186     37.        20.
     6         1040.      5.38      43.3    0.0168     49.        18.
     7         1840.      0.47      48.6    0.0170      4.        18.
     8         1840.      2.34      29.5    0.0102     13.        11.
     9         1840.      1.48      57.5    0.0196     16.        21.
    10         1840.      0.49      60.3    0.0199      5.        21.
    11         1840.      1.13      62.1    0.0205     13.        22.
    12         1840.      2.09      64.4    0.0222     25.        23.
    13         1840.      2.71      47.9    0.0173     25.        18.
    14         1840.      1.07      48.6    0.0170     10.        18.
    15         1840.      2.77      54.5    0.0193     29.        20.
    16         1840.      0.78      48.6    0.0170      7.        18.
    17         1840.      0.21      41.4    0.0145      2.        15.
    18         1840.      2.32      45.6    0.0164     21.        17.
    19         1840.      2.65      30.5    0.0123     18.        13.
    20         1840.      2.78      39.3    0.0153     23.        16.
    21         1840.      2.61      34.2    0.0132     19.        14.
    22         1840.      1.70      31.8    0.0118     11.        12.
    23         1840.      1.53      35.1    0.0128     11.        14.
    24         1840.      2.43      31.3    0.0120     16.        13.

 AVERAGE CAO GR LOG,GRNS/CUFT =    1.96

    R = 0.226

    T = 0.848

    AVG. % OFF THEORETICAL     48

    SIGMA (% OFF)              37

                     SUM       85


    CHI-SQUARE (% OFF)        153

    SIGMA(% CAO IN DUST)        5.4

    AVG.STOICH.DEVIATION      51.32

FLY ASH LOADING,GRNS/CUFT,AT STANDARD CONDITIONS - - AVERAGE=  2.01
   0.26       2.34      1.12      1.33      4.03      5.84
   0.39       1.93      0.98      0.48      0.91      2.19
   2.79       0.92      2.41      0.83      0.24      3.35
   2.98       2.91      2.41      2.12      2.11      3.34
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TEST NO. 1      DATE:            MAY 12, 1970
   SAMPLING PLANE A-A,EAST SIDE

                                  EFFECTIVE STOICHIOMETRY

SAMPLING     SO2       CAO      RATIO    STOICHIO SO2 RECOVERED  SO2 REMOVAL
LOCATION  CUFT/SEC GRNS/SEC CAO/SO2  QUAN.CAO FRACTION  CUFT    EFFICIENCY

    1       0.0144      1.     103.     0.094    0.038   0.001         0.1
    2       0.0134     21.    1604.     1.467    0.452   0.006         1.9
    3       0.0144     13.     907.     0.830    0.288   0.004         2.2
    4       0.0171     15.     864.     0.790    0.277   0.005         0.9
    5       0.0186     37.    1996.     1.827    0.527   0.010         2.5
    6       0.0168     49.    2922.     2.672    0.666   0.011         4.3
    7       0.0170      4.     254.     0.232    0.091   0.002         0.3
    8       0.0102     13.    1273.     1.164    0.380   0.004         1.6
    9       0.0196     16.     806.     0.737    0.261   0.005         0.9
   10       0.0199      5.     265.     0.242    0.095   0.002         0.3
   11       0.0205     13.     614.     0.562    0.206   0.004         0.4
   12       0.0222     25.    1137.     1.040    0.347   0.008         2.5
   13       0.0173     25.    1475.     1.349    0.425   0.007         1.7
   14       0.0170     10.     580.     0.530    0.195   0.003         0.7
   15       0.0193     29.    1503.     1.375    0.431   0.008         2.5
   16       0.0170      7.     421.     0.385    0.146   0.002         0.7
   17       0.0145      2.     112.     0.102    0.041   0.001         0.2
   18       0.0164     21.    1263.     1.155    0.377   0.006         3.3
   19       0.0123     18.    1439.     1.316    0.417   0.005         3.1
   20       0.0153     23.    1508.     1.379    0.432   0.007         2.9
   21       0.0132     19.    1416.     1.295    0.412   0.005         2.4
   22       0.0118     11.     923.     0.844    0.292   0.003         1.4
   23       0.0128     11.     834.     0.763    0.268   0.003         1.8
   24       0.0120     16.    1319.     1.207    0.390   0.005         3.2

EFFECTIVE STOICHIOMETRY = 0.942     AVERAGE POINT STOICHIOMETRY = 0.973

TEMPERATURES,DEGREES FAHRENHEIT                     AVERAGE =  2008.
 1820.      1820.      1820.      1867.      1897.      1711.
 2126.      2171.      2221.      2276.      2276.      2171.
 2052.      2126.      2096.      2126.      2126.      2052.
 1789.      1867.      1897.      1973.      2022.      1897.

DUST LOADING,GRNS/CUFT,AT STANDARD CONDITIONS
  0.45       5.30       2.79       2.92       7.70      11.22
  0.85       4.28       2.47       0.97       2.04       4.29
  5.50       1.99       5.17       1.61       0.44       5.68
  5.63       5.69       5.02       3.81       3.64       5.76

GAS VELOCITY,FT/SEC                                 AVERAGE =   43.8
  36.4       33.7       36.4       43.9       48.4       40.3
  48.0       29.5       57.5       60.3       62.1       64.4
  47.9       48.6       54.5       48.6       41.4       45.6
  30.5       39.3       34.2       31.8       35.1       31.3

LIMESTONE UTILIZED,PERCENT
   1.3        1.3        2.7        1.1        1.4        1.6
   1.4        1.4        1.2        1.0        0.7        2.4
   1.3        1.4        1.8        1.9        1.6        2.8
   2.4        2.1        1.8        1.6        2.4        2.6
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

             SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.2        DATE:            MAY 13, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                          140
   BOILER LOAD, MLBS/HR                                   990
   COAL RATE, LBS/HR                                   116476.
   LIMESTONE RATE, LBS/LBCOAL                            0.133
   INJECTION VELOCITY, FT/SEC                             132
   INJECTION ANGLE,DEGREES                                  0
   INJECTION ELEVATION                                 UPPER REAR
   LIMESTONE TYPE, BCR NO.                               2061
   PARTICLE SIZE, MICRONS                                 4.0
   STOICHIOMETRY                                         1.55
   COAL TYPE,CONTRACT NO.                                43T15
   EXCESS AIR,PERCENT -       WEST    33.3     EAST    35.5

COAL ANALYSIS - PROXIMATE        ACTUAL

               VOLATILE     FIXED
   MOISTURE     MATTER     CARBON         ASH       SULFUR
      8.3        32.6       46.6         12.5         2.6

COAL ANALYSIS - ULTIMATE

   HYDROGEN  NITROGEN     CARBON      SULFUR        ASH    MOISTURE
      4.26       1.27      68.10        2.60      12.50        8.30


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  15.1 EAST  11.4


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                  METHOD 1      METHOD 2      METHOD 3
                 WEST  EAST    WEST  EAST    WEST  EAST
                 20.6  22.9    17.5  16.8    20.1  23.1


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                  6057.           5808.          -249.

CAO MATERIALS BALANCE             8680.           6913.         -1767.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE            37.35

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  4.80  EAST  4.73
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     TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

          SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

      FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.3        DATE:          MAY 20, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                    143
   BOILER LOAD, MLBS/HR                             990
   COAL RATE, LBS/HR                             117040.
   LIMESTONE RATE, LBS/LBCOAL                      0.133
   INJECTION VELOCITY, FT/SEC                        59
   INJECTION ANGLE,DEGREES                            0
   INJECTION ELEVATION                           UPPER REAR
   LIMESTONE TYPE, BCR NO.                         2061
   PARTICLE SIZE, MICRONS                           4.5
   STOICHIOMETRY                                   1.84
   COAL TYPE,CONTRACT NO.                         43T15
   EXCESS AIR,PERCENT -      WEST   20.0    EAST   27.3

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE    FIXED
   MOISTURE    MATTER    CARBON      ASH      SULFUR
       9.6       32.2      44.9     13.3        2.2

COAL ANALYSIS - ULTIMATE

   HYDROGEN  NITROGEN    CARBON     SULFUR      ASH   MOISTURE
      4.15       1.23     66.25       2.20    13.30       9.60


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   7.7 EAST   6.8


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                METHOD 1     METHOD 2     METHOD 3
               WEST  EAST   WEST  EAST   WEST  EAST
                7.3  15.4   14.3  14.9    7.3  15.2


SO2 MATERIALS BALANCE       INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                 5150.           5093.           -57.

CAO MATERIALS BALANCE            8722.           8930.           209.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          35.91

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST   5.69   EAST   5.49
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     TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

           SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

      FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.4        DATE:          MAY 21, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                   144
   BOILER LOAD, MLBS/HR                            999
   COAL RATE, LBS/HR                            122862.
   LIMESTONE RATE, LBS/LBCOAL                     0.164
   INJECTION VELOCITY, FT/SEC                      127
   INJECTION ANGLE,DEGREES                           0
   INJECTION ELEVATION                          UPPER REAR
   LIMESTONE TYPE, BCR NO.                        2061
   PARTICLE SIZE, MICRONS                          4.4
   STOICHIOMETRY                                  3.10
   COAL TYPE,CONTRACT NO.                         81T8
   EXCESS AIR,PERCENT -      WEST   20.0     EAST   25.0

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE    FIXED
  MOISTURE    MATTER    CARBON        ASH      SULFUR
     10.1       31.6       46.7       11.6        1.6

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
     4.20       1.27      67.39       1.60     11.60      10.10


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  10.1 EAST   9.4


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
              METHOD 1      METHOD 2      METHOD 3
             WEST  EAST    WEST  EAST    WEST  EAST
             16.7  17.4    20.3  19.8    14.8  14.8


SO2 MATERIALS BALANCE        INPUT,LBS/HR    OUTPUT,LBS/HR    DIFFERENCE
                                   3932.            3805.          -126.

CAO MATERIALS BALANCE             11290.            7001.         -4289.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          44.20

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  4.86  EAST  4.69
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      TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

           SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

         FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.5        DATE:           MAY 26, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                  142
   BOILER LOAD, MLBS/HR                           990
   COAL RATE, LBS/HR                           114800.
   LIMESTONE RATE, LBS/LBCOAL                   0.171
   INJECTION VELOCITY, FT/SEC                      67
   INJECTION ANGLE,DEGREES                          0
   INJECTION ELEVATION                         UPPER REAR
   LIMESTONE TYPE, BCR NO.                       2061
   PARTICLE SIZE, MICRONS                         4.2
   STOICHIOMETRY                                 3.68
   COAL TYPE,CONTRACT NO.                        81T8
   EXCESS AIR,PERCENT -      WEST   16.7    EAST   18.0

COAL ANALYSIS - PROXIMATE       ACTUAL

            VOLATILE     FIXED
  MOISTURE   MATTER     CARBON        ASH      SULFUR
       9.8      31.5      46.3       12.4         1.4

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON    SULFUR      ASH   MOISTURE
      4.18      1.26     66.95      1.40    12.40       9.80


% LIMESTONE UTILIZED, BOILER OUTLET - WEST    6.5 EAST   7.2


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
               METHOD 1      METHOD 2      METHOD 3
             WEST  EAST    WEST  EAST    WEST  EAST
             18.5  18.7    18.5  19.2    14.8  14.8


SO2 MATERIALS BALANCE        INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                  3214.          3991.              776.

CAO MATERIALS BALANCE            10999.          7693.            -3306.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE           43.59

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST   5.38  EAST   5.33
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          TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

               SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.6       DATE:           MAY 27, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                    142
   BOILER LOAD, MLBS/HR                             986
   COAL RATE, LBS/HR                             115664.
   LIMESTONE RATE, LBS/LBCOAL                      0.126
   INJECTION VELOCITY, FT/SEC                        68
   INJECTION ANGLE,DEGREES                            0
   INJECTION ELEVATION                          LOWER REAR
   LIMESTONE TYPE, BCR NO.                         2061
   PARTICLE SIZE, MICRONS                           4.2
   STOICHIOMETRY                                   2.11
   COAL TYPE,CONTRACT NO.                          81T8
   EXCESS AIR,PERCENT -      WEST   23.9    EAST   21.7

COAL ANALYSIS - PROXIMATE      AVERAGE

            VOLATILE    FIXED
  MOISTURE   MATTER    CARBON        ASH      SULFUR
     10.0      30.8      45.9       10.7        1.8

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
     4.23      1.30      65.77       1.77      10.70      10.00


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   6.6 EAST   6.2


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                 METHOD 1      METHOD 2      METHOD 3
                WEST  EAST    WEST  EAST    WEST  EAST
                12.6  13.2    10.8  10.3    10.3  11.4


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                  4095.          4664.              569.

CAO MATERIALS BALANCE             8166.          5766.            -2400.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE              39.75

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  4.49  EAST  4.56
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     TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
          SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
       FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.7       DATE:          MAY 28, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                 140
   BOILER LOAD, MLBS/HR                          961
   COAL RATE, LBS/HR                          118879.
   LIMESTONE RATE, LBS/LBCOAL                  0.152
   INJECTION VELOCITY, FT/SEC                    130
   INJECTION ANGLE,DEGREES                         0
   INJECTION ELEVATION                       LOWER REAR
   LIMESTONE TYPE, BCR NO.                      2061
   PARTICLE SIZE, MICRONS                        4.6
   STOICHIOMETRY                                2.30
   COAL TYPE,CONTRACT NO.                       81T8
   EXCESS AIR,PERCENT -      WEST   19.2     EAST   18.3

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE    FIXED
  MOISTURE     MATTER    CARBON        ASH      SULFUR
     10.9       31.7      45.5        11.9        2.0

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON     SULFUR      ASH   MOISTURE
     4.15      1.24     66.39       2.00     11.90      10.90


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   6.5 EAST   5.2


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                 METHOD 1      METHOD 2      METHOD 3
                WEST  EAST    WEST  EAST    WEST  EAST
                13.3  14.6    13.2  11.9     9.4  11.0


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                 4755.          5596.            840.

CAO MATERIALS BALANCE           10124.          8809.          -1316.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          41.71

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.04  EAST  5.07
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          TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

                SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

            FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.8        DATE:           JUNE 2, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                   140
   BOILER LOAD, MLBS/HR                            976
   COAL RATE, LBS/HR                            117321.
   LIMESTONE RATE, LBS/LBCOAL                    0.166
   INJECTION VELOCITY, FT/SEC                       68
   INJECTION ANGLE,DEGREES                           0
   INJECTION ELEVATION                          LOWER REAR
   LIMESTONE TYPE, OCR NO.                        2061
   PARTICLE SIZE, MICRONS                          4.5
   STOICHIOMETRY                                  2.43
   COAL TYPE,CONTRACT NO.                         81T8
   EXCESS AIR,PERCENT -      WEST    20.0     EAST    23.5

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE     FIXED
  MOISTURE    MATTER      CARBON        ASH      SOLFUR
     10.6      32.7        44.7        12.0        2.1

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
     4.17       1.25      60.47       2.10     12.00      10.60


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   5.7 EAST   7.3


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
               METHOD 1      METHOD 2      METHOD 3
              WEST  EAST   WEST  EAST    WEST  EAST
              14.1  15.9   13.1  14.5    10.9  12.0


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR     DIFFERENCE
                                 4927.          6350.             1422.

CAO MATERIALS BALANCE           10912.          9202.            -1710.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE           43.66

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.05  EAST  4.93
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
              SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
           FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.9       DATE:          JULY 16, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                       140
   BOILER LOAD, MLBS/HR                                1030
   COAL RATE, LBS/HR                                 116952.
   LIMESTONE RATE, LBS/LBCOAL                          0.121
   INJECTION VELOCITY, FT/SEC                          940
   INJECTION ANGLE,DEGREES                               0
   INJECTION ELEVATION                               UPPER REAR
   LIMESTONE TYPE, BCR NO.                             2061
   PARTICLE SIZE, MICRONS                               4.7
   STOICHIOMETRY                                       1.47
   COAL TYPE,CONTRACT NO.                              81T8
   EXCESS AIR,PERCENT -      WEST   18.0    EAST   14.1

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER    CARBON        ASH      SULFUR
       8.6      32.6      45.0        13.8        2.5

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON     SULFUR       ASH   MOISTURE
      4.18      1.24     66.66       2.50     13.80       8.60


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   9.0 EAST  10.4


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
               METHOD 1      METHOD 2      METHOD 3
             WEST  EAST    WEST  EAST    WEST  EAST
             16.6  15.6    13.7  12.0    14.2  13.2


SO2 MATERIALS BALANCE         INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                   5848.          6289.             441.

CAO MATERIALS BALANCE              7929.          6744.           -1185.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          32.94

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST   6.12  EAST   6.20
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      TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

           SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

         FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.10R2    DATE:          JULY 22, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                   139
   BOILER LOAD, MLBS/HR                            979
   COAL RATE, LBS/HR                            115743.
   LIMESTONE RATE, LBS/LBCOAL                    0.166
   INJECTION VELOCITY, FT/SEC                      940
   INJECTION ANGLE,DEGREES                           0
   INJECTION ELEVATION                          UPPER REAR
   LIMESTONE TYPE, BCR NO.                        2061
   PARTICLE SIZE, MICRONS                          5.0
   STOICHIOMETRY                                  1.33
   COAL TYPE,CONTRACT NO.                         81T8
   EXCESS AIR,PERCENT -      WEST    32.9    EAST    35.5

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE    FIXED
  MOISTURE     MATTER    CARBON         ASH       SULFUR
       8.4       33.1      43.3        15.2          3.8

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
      4.13      1.21      65.53       3.80     15.20       8.40


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  10.0 EAST   9.4


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
              METHOD 1      METHOD 2       METHOD 3
            WEST  EAST    WEST  EAST    WEST  EAST
            12.5  14.4    11.5  11.4    11.6  13.1


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                  8796.          9277.             481.

CAO MATERIALS BALANCE           10765.          8965.            -1800.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          37.96

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST   6.00  EAST   5.90
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
              SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
           FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10
TEST NO.11      DATE:         JULY 23, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                 139
   BOILER LOAD, MLBS/HR                          985
   COAL RATE, LBS/HR                          114542.
   LIMESTONE RATE, LBS/LBCOAL                   0.167
   INJECTION VELOCITY, FT/SEC                    195
   INJECTION ANGLE,DEGREES                         0
   INJECTION ELEVATION                           FRONT
   LIMESTONE TYPE, BCR NO.                      2061
   PARTICLE SIZE, MICRONS                        5.0
   STOICHIOMETRY                                1.53
   COAL TYPE,CONTRACT NO.                       81T8
   EXCESS AIR,PERCENT -      WEST    31.3    EAST    29.6

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER    CARBON        ASH      SULFUR
       8.8      33.5      43.9       13.8        3.3

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
      4.19      1.22      66.39       3.30     13.80       8.80


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   8.6 EAST   7.9


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                METHOD 1      METHOD 2      METHOD 3
              WEST  EAST   WEST  EAST    WEST  EAST
              13.4   5.7   11.7   8.2    11.0   4.7


SO2 MATERIALS BALANCE          INPUT,LBS/HR   OUTPUT,LBS/HR     DIFFERENCE
                                      7560.           8999.          1439.

CAO MATERIALS BALANCE                10718.           7877.         -2840.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          40.41

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.44  EAST  5.50
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      TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
           SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
         FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.12R3    DATE:        AUGUST 4, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                    139
   BOILER LOAD, MLBS/HR                             998
   COAL RATE, LBS/HR                             114423.
   LIMESTONE RATE, LBS/LBCOAL                     0.132
   INJECTION VELOCITY, FT/SEC                       198
   INJECTION ANGLE,DEGREES                            0
   INJECTION ELEVATION                              FRONT
   LIMESTONE TYPE, BCR NO.                         2061
   PARTICLE SIZE, MICRONS                           5.0
   STOICHIOMETRY                                   1.11
   COAL TYPE,CONTRACT NO.                          81T8
   EXCESS AIR,PERCENT -      WEST   35.0    EAST   37.7

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE    FIXED
  MOISTURE     MATTER    CARBON        ASH       SULFUR
      6.3        32.8      44.5        16.4         3.6

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH    MOISTURE
     4.17       1.23      66.37       3.60     16.40        6.30


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  13.9 EAST  15.1


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
               METHOD 1      METHOD 2      METHOD 3
             WEST  EAST    WEST  EAST    WEST  EAST
             12.3   6.3    11.3   8.9    12.4   6.1


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                  8238.          7917.            -322.

CAO MATERIALS BALANCE             8463.          4975.           -3487.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE         31.08

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  6.48  EAST  6.36
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

              SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.13      DATE:          JULY 29, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                    142
   BOILER LOAD, MLBS/HR                            1007
   COAL RATE, LBS/HR                             116000.
   LIMESTONE RATE, LBS/LBCOAL                     0.128
   INJECTION VELOCITY, FT/SEC                       101
   INJECTION ANGLE,DEGREES                            0
   INJECTION ELEVATION                             FRONT
   LIMESTONE TYPE, BCR NO.                         2061
   PARTICLE SIZE, MICRONS                           4.7
   STOICHIOMETRY                                   1.76
   COAL TYPE,CONTRACT NO.                          81T8
   EXCESS AIR,PERCENT -      WEST   37.7    EAST   37.7

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER    CARBON        ASH      SULFUR
       9.1      32.3      46.1       12.5         2.2

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON    SULFUR      ASH   MOISTURE
      4.22      1.26     67.41      2.20    12.50       9.10


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   9.1 EAST   7.1


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
               METHOD 1     METHOD 2     METHOD 3
              WEST  EAST   WEST  EAST   WEST  EAST
              16.7  18.2   11.8  11.6   12.9  14.1


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                 5104.          6018.             914.

CAO MATERIALS BALANCE            8319.          6436.           -1883.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          36.46

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  4.68  EAST  4.68
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

            SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

        FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.14       DATE:          JULY 29, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                 144
   BOILER LOAD, MLBS/HR                         1000
   COAL RATE, LBS/HR                          116000.
   LIMESTONE RATE, LBS/LBCOAL                  0.157
   INJECTION VELOCITY, FT/SEC                    192
   INJECTION ANGLE,DEGREES                         0
   INJECTION ELEVATION                           FRONT
   LIMESTONE TYPE, BCR NO.                      2061
   PARTICLE SIZE, MICRONS                        4.6
   STOICHIOMETRY                                1.46
   COAL TYPE,CONTRACT NO.                       81T8
   EXCESS AIR,PERCENT -      WEST   37.7    EAST   37.7

COAL ANALYSIS - PROXIMATE       ACTUAL

            VOLATILE    FIXED
  MOISTURE   MATTER    CARBON        ASH      SULFUR
     9.1      32.3      46.1        12.5        3.3

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON    SULFUR      ASH   MOISTURE
     4.22      1.26     67.41       3.30    12.50       9.10


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   7.2 EAST   5.9


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
              METHOD 1     METHOD 2      METHOD 3
            WEST  EAST   WEST  EAST    WEST  EAST
            16.3  16.3    7.8   7.5    16.8  16.8


SO2 MATERIALS BALANCE        INPUT,LBS/HR    OUTPUT,LBS/HR    DIFFERENCE
                                 7656.            6833.           -823.

CAO MATERIALS BALANCE           10204.            7761.          -2443.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          41.31

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST   4.64   EAST   4.64
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          TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
               SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
            FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.15      DATE:         JULY 31, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                       142
   BOILER LOAD, MLBS/HR                               1004
   COAL RATE, LBS/HR                                123310.
   LIMESTONE RATE, LBS/LBCOAL                        0.118
   INJECTION VELOCITY, FT/SEC                          945
   INJECTION ANGLE,DEGREES                               0
   INJECTION ELEVATION                             UPPER REAR
   LIMESTONE TYPE, BCR NO.                            2061
   PARTICLE SIZE, MICRONS                              4.8
   STOICHIOMETRY                                      1.75
   COAL TYPE,CONTRACT NO.                             81T8
   EXCESS AIR,PERCENT -      WEST    33.3    EAST    40.0

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER    CARBON        ASH      SULFUR
      9.6      35.2      51.0        13.8        2.1

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON     SULFUR       ASH   MOISTURE
     4.17      1.19     75.10       2.10      13.80       9.60


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  12.8 EAST   9.9


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
              METHOD 1      METHOD 2      METHOD 3
             WEST  EAST   WEST  EAST   WEST  EAST
             29.6  38.3   19.4  19.7   26.2  27.3


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                 5179.          5406.            227.

CAO MATERIALS BALANCE            8153.          7911.           -242.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE            32.39

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  4.71  EAST  4.50
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

           SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

        FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.14      DATE:         JULY 29, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                      144
   BOILER LOAD, MLBS/HR                               1000
   COAL RATE, LBS/HR                                116000.
   LIMESTONE RATE, LBS/LBCOAL                        0.157
   INJECTION VELOCITY, FT/SEC                         192
   INJECTION ANGLE,DEGREES                              0
   INJECTION ELEVATION                                FRONT
   LIMESTONE TYPE, BCR NO.                           2061
   PARTICLE SIZE, MICRONS                             4.6
   STOICHIOMETRY                                     1.46
   COAL TYPE,CONTRACT NO.                            81T8
   EXCESS AIR,PERCENT -      WEST    37.7     EAST    37.7

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE     FIXED
   MOISTURE   MATTER     CARBON        ASH       SULFUR
      9.1      32.3       46.1        12.5        3.3

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH    MOISTURE
    4.22       1.26       67.41       3.30      12.50       9.10


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   7.2 EAST   5.9


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                METHOD 1     METHOD 2     METHOD 3
              WEST  EAST   WEST  EAST   WEST  EAST
              16.3  16.3    7.8   7.5   16.8  16.8


SO2 MATERIALS BALANCE         INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                 7656.          6833.           -823.

CAO MATERIALS BALANCE           10204.          7761.          -2443.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          41.31

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  4.64  EAST  4.64
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      TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
            SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
        FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10
TEST NO.15       DATE:          JULY 31, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                       142
   BOILER LOAD, MLBS/HR                               1004
   COAL RATE, LBS/HR                               123310.
   LIMESTONE RATE, LBS/LBCOAL                        0.118
   INJECTION VELOCITY, FT/SEC                          945
   INJECTION ANGLE,DEGREES                               0
   INJECTION ELEVATION                          UPPER REAR
   LIMESTONE TYPE, BCR NO.                            2061
   PARTICLE SIZE, MICRONS                              4.8
   STOICHIOMETRY                                      1.75
   COAL TYPE,CONTRACT NO.                             81T6
   EXCESS AIR,PERCENT -      WEST   33.3    EAST   40.0

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER    CARBON        ASH      SULFUR
       9.6      35.2      51.0       13.8        2.1

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
     4.17      1.19      75.10       2.10     13.80       9.60


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  12.8 EAST   9.9


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                 METHOD 1      METHOD 2      METHOD 3
               WEST  EAST    WEST  EAST    WEST  EAST
               29.6  38.3    19.4  19.7    26.2  27.3


SO2 MATERIALS BALANCE        INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                   5179.           5406.            227.

CAO MATERIALS BALANCE              8153.           7911.           -242.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE           32.39

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  4.71  EAST  4.50
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      TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
           SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
      FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10
TEST NO.16      DATE:       AUGUST 11, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                  142
   BOILER LOAD, MLBS/HR                          1001
   COAL RATE, LBS/HR                           119970.
   LIMESTONE RATE, LBS/LBCOAL                    0.160
   INJECTION VELOCITY, FT/SEC                     940
   INJECTION ANGLE,DEGREES                          0
   INJECTION ELEVATION                         UPPER REAR
   LIMESTONE TYPE, BCR NO.                       2061
   PARTICLE SIZE, MICRONS                         4.7
   STOICHIOMETRY                                  1.50
   COAL TYPE,CONTRACT NO.                         81T8
   EXCESS AIR,PERCENT -      WEST    31.3    EAST    29.6

COAL ANALYSIS - PROXIMATE       ACTUAL

           VOLATILE     FIXED
  MOISTURE   MATTER   CARBON        ASH      SULFUR
      8.9      32.1      43.4      15.6        3.2

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON    SULFUR      ASH   MOISTURE
     4.08      1.20     64.82      3.20     15.60      8.90


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  16.5 EAST  20.1


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
             METHOD 1     METHOD 2     METHOD 3
           WEST  EAST   WEST  EAST   WEST  EAST
           16.5  19.1   17.6  14.7   13.7  15.3


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                  7678.          9292.           1614.

CAO MATERIALS BALANCE            10755.          6023.          -4732.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE         36.49

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  6.29  EAST  6.36
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      TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

            SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

         FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.17       DATE:        AUGUST 11, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                     142
   BOILER LOAD, MLBS/HR                             1000
   COAL RATE, LBS/HR                              118750.
   LIMESTONE RATE, LBS/LBCOAL                      0.117
   INJECTION VELOCITY, FT/SEC                        131
   INJECTION ANGLE,DEGREES                            45
   INJECTION ELEVATION                            UPPER REAR
   LIMESTONE TYPE, BCR NO.                          2061
   PARTICLE SIZE, MICRONS                            4.8
   STOICHIOMETRY                                    1.01
   COAL TYPE,CONTRACT NO.                           81T8
   EXCESS AIR,PERCENT -      WEST    31.3    EAST    29.6

COAL ANALYSIS - PROXIMATE       ACTUAL

            VOLATILE    FIXED
  MOISTURE   MATTER    CARBON        ASH      SULFUR
      8.1      32.1      42.8       17.0         3.5

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH  MOISTURE
     4.05      1.19      54.27        3.50     17.00       8.10


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  13.0 EAST  14.5


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                 METHOD 1      METHOD 2      METHOD 3
               WEST  EAST    WEST  EAST    WEST  EAST
               16.5   8.6    15.3  14.1    16.0   8.1


SO2 MATERIALS BALANCE       INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                8312.          8848.              535.

CAO MATERIALS BALANCE           7785.          7714.              -70.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE           27.83

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  6.96  EAST  7.05
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
              SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
            FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10
TEST NO.18       DATE:        AUGUST 12, 1970

TEST CONDITIONS
   UNIT LOAD, MW                                       141
   BOILER LOAD, MLBS/HR                               1010
   COAL RATE, LBS/HR                               120379.
   LIMESTONE RATE, LBS/LBCOAL                        0.135
   INJECTION VELOCITY, FT/SEC                          131
   INJECTION ANGLE,DEGREES                              45
   INJECTION ELEVATION                            UPPER REAR
   LIMESTONE TYPE, BCR NO.                            2061
   PARTICLE SIZE, MICRONS                              4.7
   STOICHIOMETRY                                      1.77
   COAL TYPE,CONTRACT NO.                             81T8
   EXCESS AIR,PERCENT -      WEST    37.3     EAST    29.6

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER    CARBON        ASH     SULFUR
     10.5       30.3      41.7        17.5       2.4

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON    SULFUR      ASH   MOISTURE
     3.88      1.15      61.84      2.40     17.50     10.50


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  13.7 EAST  11.9


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                 METHOD 1      METHOD 2      METHOD 3
               WEST  EAST   WEST  EAST   WEST  EAST
               26.0  16.7   21.2  16.5   17.2  11.0


SO2 MATERIALS BALANCE       INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                5778.         8392.             2613.

CAO MATERIALS BALANCE           9105.         7307.            -1799.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE        30.18

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  7.03  EAST  7.38
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

             SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.19      DATE:        AUGUST 13, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                 142
   BOILER LOAD, MLBS/HR                          995
   COAL RATE, LBS/HR                          120356.
   LIMESTONE RATE, LBS/LBCOAL                  0.115
   INJECTION VELOCITY, FT/SEC                    132
   INJECTION ANGLE,DEGREES                       -45
   INJECTION ELEVATION                        UPPER REAR
   LIMESTONE TYPE, BCR NO.                      2061
   PARTICLE SIZE, MICRONS                        4.7
   STOICHIOMETRY                                1.16
   COAL TYPE,CONTRACT NO.                       81T8
   EXCESS AIR,PERCENT -      WEST   39.1    EAST   38.2

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER    CARBON       ASH      SULFUR
      7.8       32.9      45.6       13.7        3.0

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON     SULFUR       ASH   MOISTURE
     4.23      1.25     67.44       3.00      13.70       7.80


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  12.5 EAST  11.1


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
               METHOD 1     METHOD 2     METHOD 3
              WEST  EAST   WEST  EAST   WEST  EAST
              14.5  16.6   12.6  10.4   11.9  13.3


SO2 MATERIALS BALANCE        INPUT,LBS/HR    OUTPUT,LBS/HR    DIFFERENCE
                                 7221.           8602.            1380.

CAO MATERIALS BALANCE            7755.           6104.           -1651.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          31.99

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.12  EAST  5.15
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          TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
               SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
        FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10
TEST NO.20      DATE:        AUGUST 13, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                        142
   BOILER LOAD, MLBS/HR                                1000
   COAL RATE, LBS/HR                                 117500.
   LIMESTONE RATE, LBS/LBCOAL                          0.167
   INJECTION VELOCITY, FT/SEC                           132
   INJECTION ANGLE,DEGREES                              -45
   INJECTION ELEVATION                              UPPER REAR
   LIMESTONE TYPE, BCR NO.                             2061
   PARTICLE SIZE, MICRONS                               4.7
   STOICHIOMETRY                                       1.69
   COAL TYPE,CONTRACT NO.                              81T8
   EXCESS AIR,PERCENT -       WEST     39.1     EAST     38.2

COAL ANALYSIS - PROXIMATE        ACTUAL

             VOLATILE     FIXED
  MOISTURE    MATTER     CARBON         ASH       SULFUR
      7.9       33.1       44.9         14.1         3.0

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
      4.21       1.24      66.97       3.00     14.10        7.90


% LIMESTONE UTILIZED, BOILER OUTLET - WEST    9.0 EASŢ    9.0


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                  METHOD 1      METHOD 2      METHOD 3
                 WEST  EAST    WEST  EAST    WEST  EAST
                 16.6  18.7    13.5  12.9    14.2  14.3


SO2 MATERIALS BALANCE          INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                     7050.          8329.            1279.

CAO MATERIALS BALANCE               10994.          9008.           -1987.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE            39.89

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST   5.29   EAST   5.33
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           TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
                 SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
            FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.21       DATE:       AUGUST 24, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                   136
   BOILER LOAD, MLBS/HR                           1003
   COAL RATE, LBS/HR                            113425.
   LIMESTONE RATE, LBS/LBCOAL                    0.075
   INJECTION VELOCITY, FT/SEC                      134
   INJECTION ANGLE,DEGREES                         -45
   INJECTION ELEVATION                          UPPER REAR
   LIMESTONE TYPE, BCR NO.                        2061
   PARTICLE SIZE, MICRONS                          5.1
   STOICHIOMETRY                                  0.87
   COAL TYPE,CONTRACT NO.                         81T8
   EXCESS AIR,PERCENT -      WEST   16.6    EAST   16.0

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER     CARBON         ASH      SULFUR
      9.5      35.5       48.0         16.5        2.6

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
      4.04      1.13      72.62       2.60     16.50       9.50


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  10.1 EAST   7.2


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
               METHOD 1      METHOD 2      METHOD 3
             WEST  EAST    WEST  EAST    WEST  EAST
              8.5  10.8    11.5  12.0     6.5   8.2


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                  5898.           7867.          1969.

CAO MATERIALS BALANCE             4766.           7052.          2286.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE         20.30

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  6.56  EAST  6.59
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          TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
               SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
            FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.22      DATE:       AUGUST 25, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                   140
   BOILER LOAD, MLBS/HR                           1016
   COAL RATE, LBS/HR                            119000.
   LIMESTONE RATE, LBS/LBCOAL                    0.099
   INJECTION VELOCITY, FT/SEC                      131
   INJECTION ANGLE,DEGREES                           0
   INJECTION ELEVATION                          UPPER REAR
   LIMESTONE TYPE, BCR NO.                        2061
   PARTICLE SIZE, MICRONS                          4.8
   STOICHIOMETRY                                  1.76
   COAL TYPE,CONTRACT NO.                         81T8
   EXCESS AIR,PERCENT -      WEST    15.4    EAST    25.0

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE    FIXED
  MOISTURE     MATTER     CARBON        ASH      SULFUR
     10.6       30.9       43.6        14.9        1.7

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR      ASH   MOISTURE
     4.01       1.19      64.03       1.70     14.90     10.60


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  11.1 EAST  11.8


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                METHOD 1      METHOD 2      METHOD 3
               WEST  EAST    WEST  EAST    WEST  EAST
               19.4  24.3    17.2  19.5    15.0  17.3


SO2 MATERIALS BALANCE        INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                 4046.          4809.              763.

CAO MATERIALS BALANCE            6601.          5675.             -926.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          27.13

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  6.77  EAST  6.31
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       TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
            SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
        FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.23      DATE:      AUGUST 27, 1970


TEST CONDITIONS
   UNIT LOAD, MW                              140
   BOILER LOAD, MLBS/HR                      1005
   COAL RATE, LBS/HR                       116341.
   LIMESTONE RATE, LBS/LBCOAL                0.130
   INJECTION VELOCITY, FT/SEC                  68
   INJECTION ANGLE,DEGREES                      0
   INJECTION ELEVATION                     UPPER REAR
   LIMESTONE TYPE, BCR NO.                   2061
   PARTICLE SIZE, MICRONS                     4.4
   STOICHIOMETRY                             1.07
   COAL TYPE,CONTRACT NO.                    81T8
   EXCESS AIR,PERCENT -      WEST   28.8   EAST   33.8

COAL ANALYSIS - PROXIMATE      ACTUAL

          VOLATILE   FIXED
 MOISTURE  MATTER    CARBON       ASH     SULFUR
     8.6     34.9      41.5       15.0       3.7

COAL ANALYSIS - ULTIMATE

 HYDROGEN  NITROGEN    CARBON     SULFUR      ASH   MOISTURE
     4.15      1.19     65.35       3.70    15.00       8.60


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  12.5 EAST  11.0


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
             METHOD 1     METHOD 2      METHOD 3
            WEST  EAST   WEST  EAST   WEST  EAST
             6.6  11.2    8.3   8.6    5.8   9.4


SO2 MATERIALS BALANCE       INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                 8609.          9736.           1127.

CAO MATERIALS BALANCE            8474.          5350.          -3124.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          32.69

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  6.10  EAST  5.89
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         TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
               SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.24      DATE:       AUGUST 26, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                 139
   BOILER LOAD, MLBS/HR                         1008
   COAL RATE, LBS/HR                          118095.
   LIMESTONE RATE, LBS/LBCOAL                  0.180
   INJECTION VELOCITY, FT/SEC                     67
   INJECTION ANGLE,DEGREES                       -45
   INJECTION ELEVATION                        UPPER REAR
   LIMESTONE TYPE, BCR NO.                      2061
   PARTICLE SIZE, MICRONS                        4.6
   STOICHIOMETRY                                 1.70
   COAL TYPE,CONTRACT NO.                       81T8
   EXCESS AIR,PERCENT -      WEST   39.1     EAST   32.9

COAL ANALYSIS - PROXIMATE      ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER    CARBON        ASH      SULFUR
      9.9       32.5      43.9       13.7        3.2

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
     4.12       1.21      65.59       3.20     13.70       9.90


% LIMESTONE UTILIZED, BOILER OUTLET - WEST    7.6 EAST    5.6


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                   METHOD 1      METHOD 2      METHOD 3
                 WEST  EAST    WEST  EAST    WEST  EAST
                  6.3   9.0    10.7   9.8     4.7   6.7


SO2 MATERIALS BALANCE        INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                 7558.          10052.             2494.

CAO MATERIALS BALANCE           11910.          10462.            -1448.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE             42.40

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.12  EAST  5.34
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          TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
               SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.25      DATE:       AUGUST 31, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                    116
   BOILER LOAD, MLBS/HR                             856
   COAL RATE, LBS/HR                             107088.
   LIMESTONE RATE, LBS/LBCOAL                     0.174
   INJECTION VELOCITY, FT/SEC                        68
   INJECTION ANGLE,DEGREES                            0
   INJECTION ELEVATION                          UPPER REAR
   LIMESTONE TYPE, BCR NO.                         2061
   PARTICLE SIZE, MICRONS                           5.2
   STOICHIOMETRY                                   1.29
   COAL TYPE,CONTRACT NO.                     RECLAIMED
   EXCESS AIR,PERCENT -      WEST   23.5     EAST    22.1

COAL ANALYSIS - PROXIMATE       ACTUAL

            VOLATILE    FIXED
  MOISTURE   MATTER    CARBON        ASH     SULFUR
      5.5      32.1      44.3        18.1       4.0

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR      ASH   MOISTURE
      4.12      1.22      65.63       4.00    18.10       5.50

% LIMESTONE UTILIZED, BOILER OUTLET - WEST   5.1 EAST    6.7


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                  METHOD 1      METHOD 2      METHOD 3
                 WEST  EAST    WEST  EAST    WEST  EAST
                  9.3   9.2    36.1  21.8     8.9   8.7


SO2 MATERIALS BALANCE         INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                    8567.         10126.            1558.

CAO MATERIALS BALANCE              10440.         37891.           27451.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE             35.01

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST   7.87  EAST   7.95
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         TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
             SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.26      DATE:      AUGUST 31, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                  118
   BOILER LOAD, MLBS/HR                           864
   COAL RATE, LBS/HR                           105365.
   LIMESTONE RATE, LBS/LBCOAL                    0.178
   INJECTION VELOCITY, FT/SEC                     131
   INJECTION ANGLE,DEGREES                        -45
   INJECTION ELEVATION                         UPPER REAR
   LIMESTONE TYPE, BCR NO.                       2061
   PARTICLE SIZE, MICRONS                         4.8
   STOICHIOMETRY                                 1.29
   COAL TYPE,CONTRACT NO.                     RECLAIMED
   EXCESS AIR,PERCENT -      WEST    30.4    EAST    30.4

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE    FIXED
  MOISTURE     MATTER     CARBON       ASH      SULFUR
       7.2       32.9       42.2       17.7        4.2

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR      ASH   MOISTURE
     4.07       1.18      64.38       4.20    17.70       7.20


% LIMESTONE UTILIZED, BOILER OUTLET - WEST    8.7 EAST    7.9


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                   METHOD 1     METHOD 2     METHOD 3
                 WEST  EAST   WEST  EAST   WEST  EAST
                  6.5   5.0   10.3  10.5    5.7   4.3


SO2 MATERIALS BALANCE         INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                     8851.          10356.         1505.

CAO MATERIALS BALANCE               10508.           9281.        -1227.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE         36.04

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST   7.31  EAST   7.31
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            TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

                SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

             FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.27      DATE:      SEPTEMBER 2, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                     120
   BOILER LOAD, MLBS/HR                              855
   COAL RATE, LBS/HR                              101333.
   LIMESTONE RATE, LBS/LBCOAL                       0.072
   INJECTION VELOCITY, FT/SEC                         69
   INJECTION ANGLE,DEGREES                           -45
   INJECTION ELEVATION                            UPPER REAR
   LIMESTONE TYPE, BCR NO.                          2061
   PARTICLE SIZE, MICRONS                            5.7
   STOICHIOMETRY                                    1.10
   COAL TYPE,CONTRACT NO.                           81T8
   EXCESS AIR,PERCENT -      WEST   11.0     EAST    11.9

COAL ANALYSIS - PROXIMATE        ACTUAL

             VOLATILE    FIXED
  MOISTURE    MATTER    CARBON         ASH       SULFUR
      9.4      31.4      44.6          14.6        2.3

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON      SULFUR        ASH   MOISTURE
      4.09      1.22      65.34        2.30      14.60       9.40


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  11.3 EAST  10.2


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                    METHOD 1      METHOD 2       METHOD 3
                  WEST   EAST   WEST   EAST    WEST   EAST
                  12.8    9.4    9.6   10.4    11.5    8.7


SO2 MATERIALS BALANCE        INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                 4661.           4981.             320.

CAO MATERIALS BALANCE            4088.           3715.            -373.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE            21.65

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST   6.81   EAST   6.77
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     TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

         SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

      FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.28       DATE:      SEPTEMBER 3, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                     117
   BOILER LOAD, MLBS/HR                              857
   COAL RATE, LBS/HR                               97904.
   LIMESTONE RATE, LBS/LBCOAL                      0.073
   INJECTION VELOCITY, FT/SEC                        135
   INJECTION ANGLE,DEGREES                             0
   INJECTION ELEVATION                            UPPER REAR
   LIMESTONE TYPE, BCR NO.                          2061
   PARTICLE SIZE, MICRONS                            5.7
   STOICHIOMETRY                                    1.13
   COAL TYPE,CONTRACT NO.                           81T8
   EXCESS AIR,PERCENT -      WEST   28.2     EAST   26.5

COAL ANALYSIS - PROXIMATE       ACTUAL

            VOLATILE    FIXED
  MOISTURE   MATTER    CARBON          ASH       SULFUR
      9.8      31.8      45.1          13.3         2.5

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR        ASH   MOISTURE
     4.14       1.23      66.11       2.50      13.30       9.80


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  13.8 EAST  12.4


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                 METHOD 1     METHOD 2     METHOD 3
               WEST  EAST   WEST  EAST   WEST  EAST
               13.6  12.2   12.9  12.7   11.9  11.1


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR     DIFFERENCE
                                 4895.          5267.              372.

CAO MATERIALS BALANCE            4004.          4167.              163.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          23.52

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.36  EAST  5.42
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          TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
              SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
           FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.29      DATE:     SEPTEMBER 4, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                      78
   BOILER LOAD, MLBS/HR                              571
   COAL RATE, LBS/HR                               67087.
   LIMESTONE RATE, LBS/LBCOAL                      0.048
   INJECTION VELOCITY, FT/SEC                        136
   INJECTION ANGLE,DEGREES                             0
   INJECTION ELEVATION                           UPPER REAR
   LIMESTONE TYPE, BCR NO.                          2061
   PARTICLE SIZE, MICRONS                            5.0
   STOICHIOMETRY                                    0.86
   COAL TYPE,CONTRACT NO.                        UNKNOWN
   EXCESS AIR,PERCENT -      WEST   28.0      EAST   27.0

COAL ANALYSIS - PROXIMATE       ACTUAL

             VOLATILE     FIXED
  MOISTURE    MATTER     CARBON        ASH      SULFUR
      8.4       32.9       45.9       12.8        1.7

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
     4.24       1.26      67.71       1.70     12.80       8.40


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  17.0 EAST  12.3


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                   METHOD 1     METHOD 2     METHOD 3
                 WEST  EAST   WEST  EAST   WEST  EAST
                 18.2  18.1   16.4  16.2   14.5  13.0


SO2 MATERIALS BALANCE       INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                  2281.           2893.           612.

CAO MATERIALS BALANCE             1804.           2288.           483.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          17.36

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.17  EAST  5.20
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      TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

          SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

      FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.1A      DATE:       AUGUST 18, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                 138
   BOILER LOAD, MLBS/HR                          995
   COAL RATE, LBS/HR                          119927.
   LIMESTONE RATE, LBS/LBCOAL                  0.128
   INJECTION VELOCITY, FT/SEC                      0
   INJECTION ANGLE,DEGREES                         0
   INJECTION ELEVATION                    LOWER REAR
   LIMESTONE TYPE, BCR NO.                      2061
   PARTICLE SIZE, MICRONS                        5.1
   STOICHIOMETRY                                1.44
   COAL TYPE,CONTRACT NO.                       81T8
   EXCESS AIR,PERCENT -     WEST   29.2    EAST   25.4

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE     FIXED
  MOISTURE     MATTER     CARBON        ASH      SULFUR
      10.3       32.3       44.2       13.2        2.7

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN     CARBON     SULFUR       ASH   MOISTURE
      4.13      1.22      65.70       2.70     13.20      10.30


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   6.1 EAST   7.4


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                    METHOD 1      METHOD 2      METHOD 3
                  WEST  EAST    WEST  EAST    WEST  EAST
                  11.6  14.7     7.0   5.9     8.6  10.9


SO2 MATERIALS BALANCE       INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                   6476.          8115.          1639.

CAO MATERIALS BALANCE              8601.          5467.         -3133.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE         35.20

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.27  EAST  5.41
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

              SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.2A      DATE:    SEPTEMBER 10, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                    138
   BOILER LOAD, MLBS/HR                            1003
   COAL RATE, LBS/HR                             117286.
   LIMESTONE RATE, LBS/LBCOAL                     0.076
   INJECTION VELOCITY, FT/SEC                       133
   INJECTION ANGLE,DEGREES                            0
   INJECTION ELEVATION                          UPPER REAR
   LIMESTONE TYPE, BCR NO.                         2061
   PARTICLE SIZE, MICRONS                           5.1
   STOICHIOMETRY                                   1.11
   COAL TYPE,CONTRACT NO.                          81T8
   EXCESS AIR,PERCENT -     WEST   32.1    EAST   35.5

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE    FIXED
   MOISTURE    MATTER    CARBON        ASH      SULFUR
        9.0      32.2      44.9       13.9         2.1

COAL ANALYSIS - ULTIMATE

   HYDROGEN  NITROGEN     CARBON     SULFUR        ASH   MOISTURE
     4.15       1.23      66.25       2.10      13.90       9.00


% LIMESTONE UTILIZED, BOILER OUTLET - WEST  12.2 EAST  10.3


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                  METHOD 1      METHOD 2      METHOD 3
                 WEST  EAST    WEST  EAST    WEST  EAST
                 20.2  13.8    19.0  16.6    17.1  11.3


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR     DIFFERENCE
                                 4926.          5662.              736.

CAO MATERIALS BALANCE            4994.          6815.             1821.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          23.45

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.51  EAST  5.38
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     TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION
          SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS
       FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.4A      DATE:    SEPTEMBER 11, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                139
   BOILER LOAD, MLBS/HR                        1040
   COAL RATE, LBS/HR                         121016.
   LIMESTONE RATE, LBS/LBCOAL                 0.087
   INJECTION VELOCITY, FT/SEC                   132
   INJECTION ANGLE,DEGREES                        0
   INJECTION ELEVATION                       UPPER REAR
   LIMESTONE TYPE, BCR NO.                     2061
   PARTICLE SIZE, MICRONS                       4.3
   STOICHIOMETRY                               1.39
   COAL TYPE,CONTRACT NO.                  RECLAIMED
   EXCESS AIR,PERCENT -     WEST   20.7    EAST   27.3

COAL ANALYSIS - PROXIMATE      ACTUAL

            VOLATILE    FIXED
  MOISTURE   MATTER    CARBON       ASH     SULFUR
      9.1      33.3      43.7       13.9       1.9

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON     SULFUR      ASH   MOISTURE
      4.16      1.22     66.05       1.90     13.90      9.10


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   8.0 EAST   6.9


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
               METHOD 1      METHOD 2      METHOD 3
             WEST  EAST    WEST  EAST    WEST  EAST
             27.4  18.4    14.5  14.5    21.7  14.2


SO2 MATERIALS BALANCE       INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                 4599.          5340.            741.

CAO MATERIALS BALANCE            5899.          7826.           1927.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          25.96

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.99  EAST  5.71
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      TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

           SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

      FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.6A      DATE:       AUGUST 20, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                     137
   BOILER LOAD, MLBS/HR                             1005
   COAL RATE, LBS/HR                              127814.
   LIMESTONE RATE, LBS/LBCOAL                      0.105
   INJECTION VELOCITY, FT/SEC                        69
   INJECTION ANGLE,DEGREES                            0
   INJECTION ELEVATION                          LOWER REAR
   LIMESTONE TYPE, BCR NO.                          2061
   PARTICLE SIZE, MICRONS                            4.4
   STOICHIOMETRY                                    1.19
   COAL TYPE,CONTRACT NO.                           81T8
   EXCESS AIR,PERCENT -      WEST   23.5    EAST   22.8

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE    FIXED
   MOISTURE    MATTER    CARBON        ASH      SULFUR
        8.2      31.7      42.1       18.0         2.6

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON     SULFUR      ASH   MOISTURE
      3.99      1.17     63.32       2.60    18.00       8.20


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   8.6 EAST   9.5


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
               METHOD 1     METHOD 2     METHOD 3
              WEST  EAST   WEST  EAST   WEST  EAST
               5.4   8.6   10.9   9.9    4.3   6.9


SO2 MATERIALS BALANCE        INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                  6646.           8328.          1682.

CAO MATERIALS BALANCE             7519.           6675.          -845.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE          24.63

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  7.95  EAST  7.99
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

              SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.7A      DATE:      AUGUST 19, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                    139
   BOILER LOAD, MLBS/HR                            1014
   COAL RATE, LBS/HR                             125734.
   LIMESTONE RATE, LBS/LBCOAL                     0.129
   INJECTION VELOCITY, FT/SEC                       132
   INJECTION ANGLE,DEGREES                            0
   INJECTION ELEVATION                           LOWER REAR
   LIMESTONE TYPE, BCR NO.                         2061
   PARTICLE SIZE, MICRONS                           4.8
   STOICHIOMETRY                                   1.72
   COAL TYPE,CONTRACT NO.                          81T8
   EXCESS AIR,PERCENT -      WEST   21.6    EAST   17.3

COAL ANALYSIS - PROXIMATE       ACTUAL

            VOLATILE    FIXED
  MOISTURE   MATTER    CARBON        ASH      SULFUR
      9.5      32.2      44.7        13.6        2.3

COAL ANALYSIS - ULTIMATE

  HYDROGEN  NITROGEN    CARBON     SULFUR       ASH   MOISTURE
     4.14      1.23     66.07       2.30      13.60       9.50


% LIMESTONE UTILIZED, BOILER OUTLET - WEST   6.1 EAST   6.9


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
              METHOD 1      METHOD 2      METHOD 3
             WEST  EAST    WEST  EAST    WEST  EAST
             14.1  14.9    11.3  11.2    10.9  11.2


SO2 MATERIALS BALANCE       INPUT,LBS/HR   OUTPUT,LBS/HR    DIFFERENCE
                                5784.          6984.            1201.

CAO MATERIALS BALANCE           9088.          8809.            -279.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE         34.70

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-  WEST  5.77  EAST  5.96
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        TENNESSEE VALLEY AUTHORITY - DIVISION OF POWER PRODUCTION

           SULFUR OXIDE REMOVAL FROM POWER PLANT STACK GAS

          FULL-SCALE LIMESTONE INJECTION TESTS AT SHAWNEE UNIT 10

TEST NO.8A      DATE:       AUGUST 19, 1970


TEST CONDITIONS
   UNIT LOAD, MW                                 140
   BOILER LOAD, MLBS/HR                         1010
   COAL RATE, LBS/HR                          125734.
   LIMESTONE RATE, LBS/LBCOAL                  0.159
   INJECTION VELOCITY, FT/SEC                     68
   INJECTION ANGLE,DEGREES                         0
   INJECTION ELEVATION                        LOWER REAR
   LIMESTONE TYPE, BCR NO.                      2061
   PARTICLE SIZE, MICRONS                        4.5
   STOICHIOMETRY                                2.01
   COAL TYPE,CONTRACT NO.                       81T8
   EXCESS AIR,PERCENT -      WEST    23.5    EAST    22.1

COAL ANALYSIS - PROXIMATE       ACTUAL

              VOLATILE     FIXED
   MOISTURE    MATTER     CARBON        ASH       SULFUR
        9.2      31.8       45.0       14.0          2.4

COAL ANALYSIS - ULTIMATE

   HYDROGEN   NITROGEN     CARBON     SULFUR       ASH    MOISTURE
       4.13       1.23      66.02       2.40     14.00        9.20


% LIMESTONE UTILIZED, BOILER OUTLET - WEST    7.4 EAST    6.5


SO2 REMOVAL EFFICIENCY,%,BOILER OUTLET
                METHOD 1      METHOD 2      METHOD 3
              WEST  EAST    WEST  EAST    WEST  EAST
              13.6  14.7    14.1  12.3    10.8  11.2


SO2 MATERIALS BALANCE        INPUT,LBS/HR    OUTPUT,LBS/HR     DIFFERENCE
                                  6035.           7497.           1462.

CAO MATERIALS BALANCE            11201.          10037.          -1164.

THEORETICAL CAO IN DUST,%,SAMPLING PLANE           38.89

THEORETICAL FLY ASH,GRNS/CUFT,SAMPLING PLANE-   WEST   5.87   EAST   5.93
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APPENDIX E

Instantaneous Dust Distribution Studies

APPENDIX E

Instantaneous Dust Distribution via Holography

Use of the technique in the region of interest (Plane A-A, 376-foot elevation) was desired but the absence of opposing ports required investigation of laser back scatter through a single port or recording side scatter by the combination of two of the several existing ports at this elevation. Mathematical modeling and laboratory tests were performed. Preliminary light scattering measurements with a continuous wave helium-neon laser indicated that the limestone distribution at Plane A-A was not spatially uniform nor was the distribution constant or repetitive with time. However, the same observation was made with fly ash alone, and since the scattered light intensity was seen to increase by a factor of about 2 with limestone addition, it appeared that the limestone and fly ash were moving together through the boiler.

Effort was discontinued at that time primarily due to current limitations of the technique for application to the boiler. Attenuation of light scattered in the backward and side directions greatly limited the depth of boiler penetration, and particle velocity components due to turbulence, etc., were expected to blur the quality of holograms. In addition, particle number density could only be estimated within a factor of 2 and no technique was available to distinguish between lime and fly ash.

Although these techniques indicated some potential for determining instantaneous concentrations of lime in fly ash, additional development efforts were required. This fact coupled with the expected lack of correlating SO_2 concentration data and the conclusion that furnace turbulence controls dust distribution led to termination of this activity.

Lasers have been used previously to study rocket exhaust conditions but holograms produced at Shawnee are believed to be the first obtained in a boiler furnace.

The following paragraphs and figures are taken directly from TRW Report No. 14103-6001-RO-00. (See reference E-1.)

3.3 TWO-BEAM HOLOCAMERA

The Phase III holography studies conducted at the 365-foot elevation of Unit 10 utilized a two-beam transmission holocamera designed to record not the direct transmitted beam but instead, low angle forward scattered light. The two-beam holocamera differed from the Gabor setup in that the reference illumination was physically removed from the scene volume and passed around the outside of the boiler with the use of additional optics. The reference illumination, termed the "reference beam" is incident on the holographic plate in an unmodified state. As such, it is readily duplicated and facilitates reconstruction of the developed plate.

Application of a two-beam holographic technique proved absolutely essential in studying particulate matter dispersed over large distances in the operating boiler. Thermal gradients, some indication of turbulence and the presence of large ensembles of particles, heavily attenuated the laser light (scene beam) passing through the boiler. Single-beam or Gabor holography is dependent upon a portion of the illumination passing through the scene in an unmodified state. This unmodified portion of the illumination serves as the reference beam which, when duplicated, reconstructs the recorded scene. In the case of the boiler studies, the heavy attenuation and modification of the laser beam encoded all of the illumination making it impossible to produce a meaningful reconstruction.

The two-beam holocamera configuration eventually selected for work at the boiler is a modification of more conventional transmission holocamera arrangements. The particles contained within the recorded scene volume are not imaged directly onto the holographic plate. Rather, the presence of particles in the scene is detected by scattered light.

Verification of the low angle forward scattered light holocamera technique was first accomplished under the separate sponsorship of the TRW independent research program. The holographic arrangement used during these early tests is shown schematically in Figure 14. The arrangement utilized a 5-inch-diameter collimating telescope, two front-surface mirrors, a glass wedge beam splitter and a corner prism. The light beam from the pulsed ruby laser was directed through the beam splitter and corner prism and projected across a scene volume of approximately 45 feet. The unexpanded scene beam was purposely directed so as not to impinge on the holographic plate. The wedge beam splitter diverted about 4 percent of the light energy into the collimating telescope to form the 5-inch-diameter reference beam. The reference illumination was directed around the scene volume. The two front-surface mirrors directed the beam onto the hologram plate at an angle of nearly 10 degrees. In contrast, the scene beam (as seen in the diagram of Figure 14) consisted only of that portion of the light scattered at a low forward angle from objects placed to intercept the unexpanded laser beam. The technique is relatively independent of the temporal coherence of the ruby laser.

The apparatus described above was used to demonstrate the feasibility of recording forward scattered light on holographic plates using a conventional Q-switched ruby laser. A series of tests was conducted in which scattered light from tufts of cotton, glass fibers and chalk dust was successfully recorded. The results of these tests are described in Section 4. Verification of the technique led to the design and installation of a scattered light transmission holocamera at elevation 365 feet on the Unit 10 boiler.

The holocamera optical component arrangement for the Phase III tests at elevation 365 feet on Unit 10 is shown in the plan view diagram of Figure 15a. The pulsed ruby laser illuminator for the holocamera was installed on a shelf positioned approximately 8 feet above the ground floor elevation of 345 feet. This installation is shown in Figure 16. The proximity of the laser to the boiler and holocamera components is shown in Figure 15b which is a perspective drawing of the test setup. From this illustration, it is seen that light was passed from the laser source to the beam splitter box (refer to Figure 15) by means of a periscope arrangement.

The laser input beam was directed into a horizontal plane at the desired boiler port elevation (~365 feet) by the periscope. The beam next entered the first optical package which consisted of a prism (No. 3), wedge beam splitter assembly and a collimating telescope. Referring to Figure 15, it will be seen that a portion of the laser input beam passed through the beam splitter assembly and proceeded directly across the front (south) side of Unit 10 to a prism box placed before the inlet port of the boiler. The laser beam is directed by the final reflector (prism No. 4) so as to enter the boiler and traverse the 24 feet of combustion volume. This last prism was set so that the light just missed the exit port on the far side or rear north wall. As in the Figure 14 test configuration, the laser beam did not fall directly on the holographic plate. Particles within the illuminating beam scattered light from the beam. Some of the light scattered at low angles in the forward direction emerged from the rear port and fell on the holographic plate to form the scene beam.

The reference illumination is formed by reflecting a portion of the laser light at the wedge beam splitter (Figure 15). The reference beam is passed through a negative lens and expanded to a 5-inch-diameter and then collimated. With the reference beam expanded to illuminate the holographic plate, it is passed by two front surface mirrors to the plate at an angle of 15 degrees with respect to the nominal axis of the emerging scene light. The angle of separation between the scene and reference beams is not critical. A design value of 10 to 30 degrees was selected as providing adequate viewing angle separation (on reconstruction) and at the same time simplify the tasks of camera and mirror mounting and of matching the optical path lengths of the scene and reference beams.

The camera and shutter assembly shown in Figure 17 is designed to accept standard 4 x 5 photographic film or plate holders. As described earlier in Section 3.2, it is fitted with two mechanical shutters, a slow-acting capping shutter which helps to protect internal parts from dust and radiant heat, and a fast-acting "focal-plane" shutter. Each time an exposure is to be made, the following sequence of events is typical:

- The film holder is loaded into the shutter mechanism, and the dark slide pulled.
- The laser flashlamp capacitor banks are charged.
- The capping shutter is opened by energizing its electrical solenoid.
- The focal-plane shutter is tripped by energizing its solenoid. A microswitch operated from a cam on the focal-plane shutter mechanism sends a trigger pulse to the laser power supply at the instant the focal-plane shutter is fully open. Laser flash duration is approximately 50 nsec; total exposure of the film to flame light is approximately 50 msec before the focal plane shutter is completely closed again.
- The dark slide is replaced and the exposed film is either removed to the dark room for processing or stored for later processing.

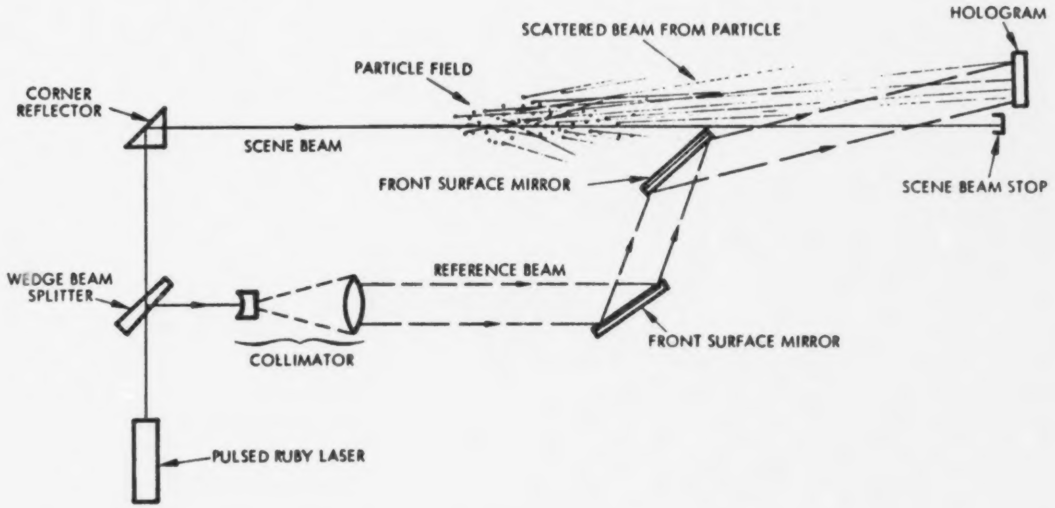

Figure 14. Schematic diagram of two-beam scattered light holocamera

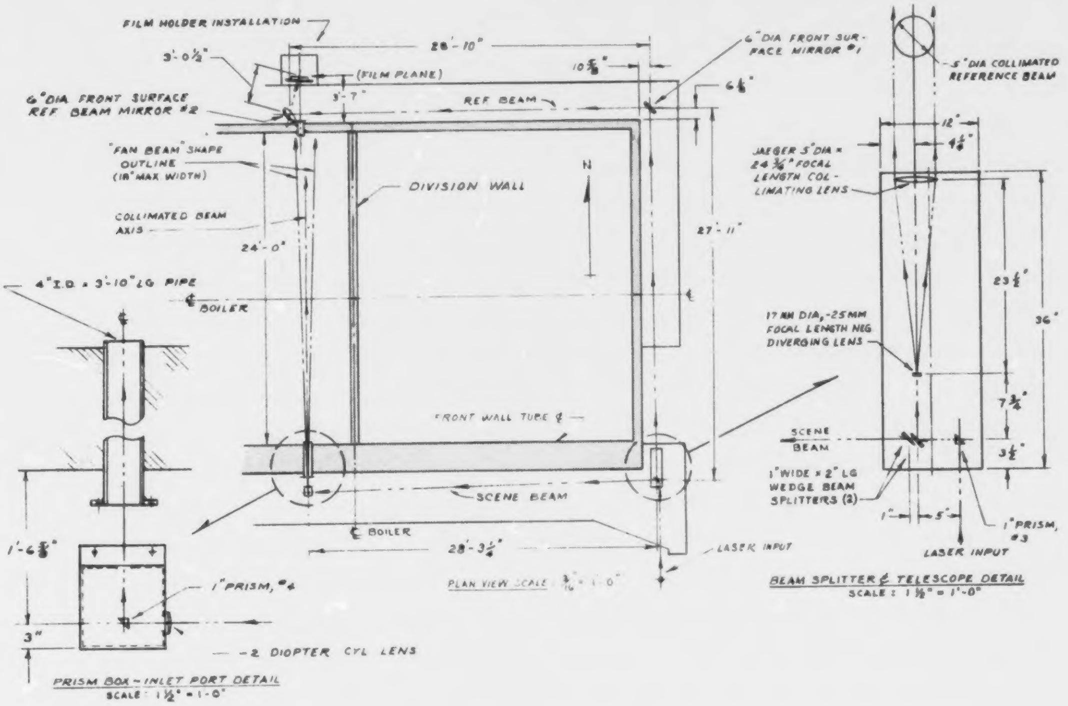
FILM HOLDER INSTALLATION
28'-10"
3'-0½"
(FILM PLANE)
10⅝"
6⅛"
6" DIA FRONT SURFACE MIRROR #1
6" DIA FRONT SURFACE REF BEAM MIRROR #2
3'-7"
REF BEAM
"FAN BEAM" SHAPE OUTLINE (18" MAX WIDTH)
DIVISION WALL
N
COLLIMATED BEAM AXIS
24'-0"
27'-11"
4" I.D. × 3'-10" LG PIPE
℄ BOILER
FRONT WALL TUBE ℄
SCENE BEAM
℄ BOILER
28'-3¼"
LASER INPUT
PLAN VIEW SCALE 3/16" = 1'-0"
1'-6⅝"
1" PRISM, #4
3"
-2 DIOPTER CYL LENS
PRISM BOX - INLET PORT DETAIL
SCALE: 1½" = 1'-0"
5" DIA COLLIMATED REFERENCE BEAM
12"
4½"
JAEGER 5" DIA × 24 3/16" FOCAL LENGTH COLLIMATING LENS
23½"
36"
17 MM DIA, -25 MM FOCAL LENGTH NEG DIVERGING LENS
7¾"
SCENE BEAM
3½"
1" WIDE × 2" LG WEDGE BEAM SPLITTERS (2)
1"
5"
1" PRISM, #3
LASER INPUT
BEAM SPLITTER & TELESCOPE DETAIL
SCALE: 1½" = 1'-0"

Figure 15a. Plan view of two-beam holocamera installation at elevation 365 feet

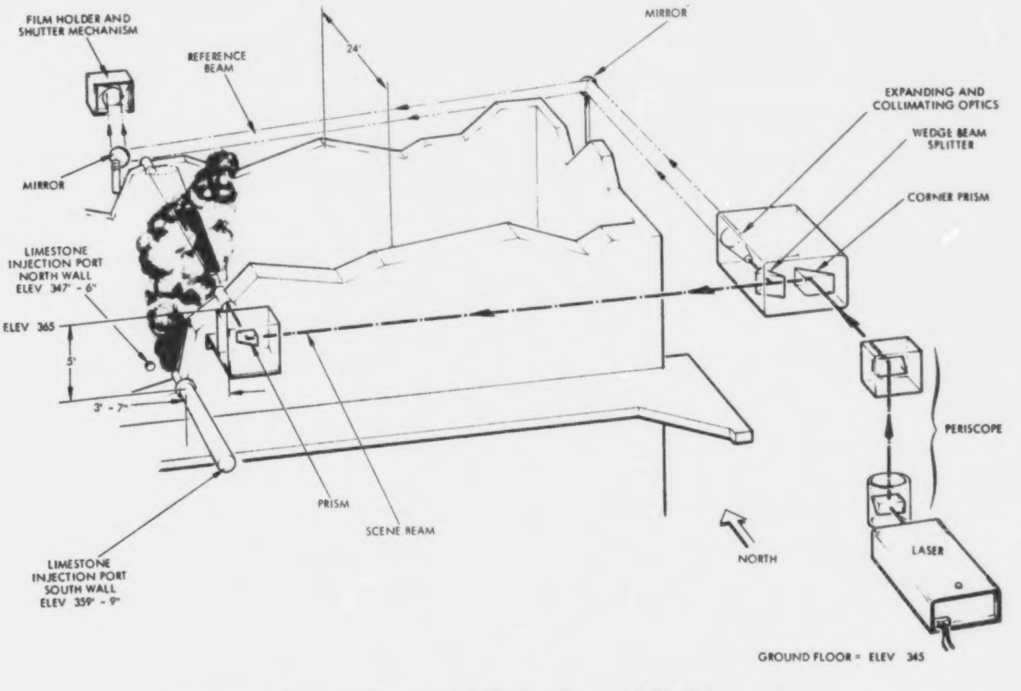
FILM HOLDER AND SHUTTER MECHANISM
REFERENCE BEAM
24'
MIRROR
EXPANDING AND COLLIMATING OPTICS
WEDGE BEAM SPLITTER
CORNER PRISM
MIRROR
LIMESTONE INJECTION PORT NORTH WALL ELEV 347' - 6"
ELEV 365
5'
3' - 7"
PERISCOPE
PRISM
SCENE BEAM
NORTH
LASER
LIMESTONE INJECTION PORT SOUTH WALL ELEV 359' - 9"
GROUND FLOOR = ELEV 345

Figure 15b. Perspective view of holocamera installation at Unit 10

Filter Tape Sampler Investigation

The second approach to determine limestone distribution in the furnace was by a moving paper tape dust sampler. This involved mounting a sampler at the end of a water-cooled probe, aspirating flue gas across the moving paper tape and analyzing the concentration of deposited dust. This work was done early in 1971 in connection with Phase II, Dust Distribution Studies.

Equipment consisted of a fractional hp motor and tape holder for movement of the tape across sampling heads into which the 26-foot long tube entered. Aspirating air and a small cyclone separator were used as in the normal probe configuration. All this equipment was attached to the working end of the probe. Testing was performed with isokinetic gas sampling up to 4 CFM at 160 °F and 1 atmosphere. Tape 1.5 inches wide was used at speeds up to 100" per minute without loss of sample from the tape but higher speeds caused trouble and some loss of sample. Testing was carried out with and without limestone injection to the boiler. Considerable effort was spent in sizing clearance between sampling heads to prevent scraping off deposits. This became more critical as course grind limestone, still below about 7 microns, was injected as compared to fine grind limestone. Air leakage around the sampling head would increase also for coarse size limestone use.

Development problems concerned (1) tape strength which limits the volume of gas that can be drawn through the tape, (2) detrimental effects of large size particles, (3) electrical problems with tape drive, (4) particle retention on the tape, (5) expense of analyzing dust density on the tape by atomic absorption technique, (6) and interpretation of results. Analysis of tapes was done by TVA and of the data by EPA. One component analysis, say for calcium, would cost about $1.50 per determination. The time schedule along with development problems mentioned above resulted in termination of further effort on this technique. (See reference E-2.)

Limestone Distribution Index - Sigma

Early study was given to analytical techniques that would be suitable for expressing the quality of limestone distribution *vis-a-vis* the presence of sulfur dioxide in furnace gas.

The results of the dust distribution study can best be compared by use of an index to relate the quantities of dust and sulfur dioxide across the sampling plane. Limestone will be perfectly distributed relative to sulfur dioxide in the boiler if each molecule of sulfur dioxide has equal opportunity to react with a particle of limestone. The development of an index will be based on this definition with perfect distribution equal to unity. It will be assumed that the velocity, temperature, dust loading, and sulfur dioxide concentration at each sampling point is typical of the area of the sampling plane represented by that point. By summation of areas, the total amounts of sulfur dioxide and limestone can be determined and the actual amounts at each point compared with prorated portions of the total. A simple correlation coefficient between the observed distribution and the theoretical based on the amount of sulfur dioxide will be expressed as the distribution index.

The standard equation for the correlation coefficient is:

$$R = \frac{\Sigma XY - n\bar{X}\bar{Y}}{\sqrt{(\Sigma X^2 - n\bar{X}^2)(\Sigma Y^2 - n\bar{Y}^2)}}$$

X = Limestone distribution needed based on sulfur dioxide distribution

Y = actual limestone distribution

n = number of sampling points

This calculation will be made with a computer. The calculation for the example case is shown in Table 1.

Values of the distribution index will range from plus 1 to minus 1 with 1 indicating the limestone is distributed exactly like the sulfur dioxide. A value of minus 1 would indicate the highly unlikely situation of complete segregation of limestone and sulfur dioxide.

It is anticipated that grain loading (grns/ft^3), SO_2 (ppm) and gas velocity (ft/sec) will be measured at several sampling points in each sampling plane. As an example, assume there will be six equally spaced sampling points in a test plane. (Figure 1) Table 1 shows the hypothetical grain loading, SO_2, and gas velocity at each sampling point. If the velocity, grain loading, and SO_2 data collected at each of the sampling points are typical of the values for one square foot in this area of the duct, then by multiplying the velocity (column 4) by the grain loading (column 3) one obtains the total grains of limestone passing through a square foot of the duct each second at each sampling location (column 6).

By converting ppm SO_2 to a fraction and multiplying it by the velocity, one can determine the number of cubic feet of SO_2 passing each sampling point in a second. This is shown in column 5.

The total grains of limestone passing all sampling points (534) can be prorated in the same fashion as the distribution of SO_2 at each point shown in column 5. Column 7 shows this proration. To the extent that columns 6 and 7 differ, the distribution is less than perfect.

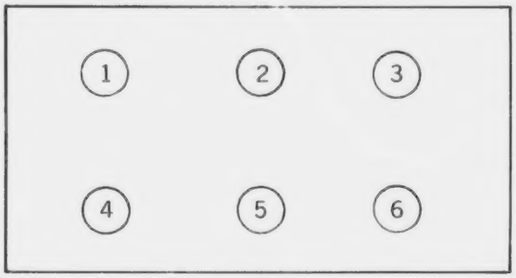

Figure 1
Hypothetical Sampling Location

Table 1

Limestone Distribution Index

(1) Sampling Location	(2) SO$_2$ ppm	(3) Limestone Grain Loading Grns/ft^3	(4) Velocity ft/sec	(5) SO$_2$ ft^3/sec	(6) Y Limestone Grns/sec	(7) X Theoretical Limestone Grns/sec*
1	2000	1.0	45	.0900	45	63
2	2500	0.8	70	.1750	56	122
3	2100	1.2	50	.1050	60	73
4	1900	1.7	50	.0950	85	66
5	2700	2.0	72	.1944	144	136
6	2200	3.0	48	.1056	144	74
				.7650	534	534

Correlation Coefficient:

$$\Sigma X^2 = 63^2 + 122^2 + 73^2 + 66^2 + 136^2 + 74^2 = 52{,}510$$

$$\Sigma Y^2 = 45^2 + 56^2 + 60^2 + 85^2 + 144^2 + 144^2 = 57{,}458$$

$$\Sigma XY = (63)(45)+(122)(56)+(73)(60)+(66)(85)+(136)(144)+(74)(144) = 49{,}897$$

$$\bar{X}=\bar{Y} = 534/6 = 89$$

$$R = \frac{\Sigma XY - nXY}{\sqrt{(\Sigma X^2 - n\bar{X}^2)(\Sigma Y^2 - n\bar{Y}^2)}} = \frac{49897 - (6)(8\text{[illegible]}(89)}{\sqrt{[52510-(6)(89)^2][\text{[illegible]}458-6(89)^2]}}$$

$$R = \frac{49897 - 47526}{\sqrt{(52510-47526)(57{,}458-47526)}} = \frac{2371}{7036} = .337$$

---

*Based on distribution of SO$_2$.

References

E-1 Mathews, B. J. and R. F. Kemp, "Holographic Determination of Injected Limestone Distribution in Unit 10 of the Shawnee Power Plant," *TRW Report* No. 14103-6001-RO-00, June 1970.

E-2 Williams, T., "Progress in Development of Filter Tape Sampler and Procedure," TVA internal report dated March 25, 1971.

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APPENDIX F

Limestone Injection Effects on Solids Collection System

APPENDIX F

APPENDIX F

Report and Analysis Of Field Tests At Shawnee Station Of TVA, Including A Techno-Economic Evaluation Of Options For Maintaining The Stack Emission Rate With Limestone Injection Equivalent To A Baseline Of No Limestone Injection

Contract No. CPA 22-69-139

Particulates Collection Study
TVA Dry Limestone Tests

Prepared For:
THE ENVIRONMENTAL PROTECTION AGENCY
Durham, North Carolina 27701

Prepared by:

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October 31, 1972

ABSTRACT

A particulate control system consisting of a mechanical cyclone-electrostatic precipitator combination has been evaluated on a full-scale boiler without and with limestone injection (dry) into the boiler for sulfur oxide removal.

The main objective of the study was to determine the effects of dry additive injection on the particulate control equipment and evaluate system modification alternatives including a cost benefit analysis that will maintain stack emissions with injection equivalent to about 2.7% sulfur and 10% ash coal-firing without injection.

Two separate test programs by Cottrell Environmental Systems were conducted, one in December 1969 which quantified the collection system on coal-firing only to serve as a baseline and the other in July 1971 in which coal sulfur and flue gas temperature, along with limestone particle size and amount injected were studied at two levels. A third test program by the Tennessee Valley Authority in the summer of 1970 has been used to establish the baseline conditions for the electrostatic precipitator and boiler flue gas. Mechanical collector performance did not vary substantially whether fly ash alone was collected or in combination with coarse or fine limestone. Efficiencies measured were in the 50 to 60% range depending upon pressure loss across the collector. Therefore, the overall efficiency of the dust collection equipment was a significant function of the precipitator performance and inlet loading only. In general, as expected, the electrostatic precipitator performance was adversely affected by limestone injection. It was found that the precipitation rate parameter without and with limestone injection was mainly a function of corona power density input, and that the power level and therefore the performance reached without excessive sparking was lower in the limestone injection cases.

The average particulate emission rate and flue gas conditions found on No. 10 boiler at Shawnee Station of TVA with the presently installed dust collection equipment were 412 lbs/hr and 570,000 cfm at 309° F. Cost estimates for size modification to the presently installed precipitator to maintain baseline emission with limestone injection have been considered for flue gas temperatures into the precipitator of 250, 309, and 600F. Other options such as gas conditioning and precipitator energization modifications have been discussed but since actual performance data for these alternatives was beyond the scope of this experimental program, only speculative comments have been made as to expected results. For coarse limestone injection, the present precipitator on boiler No. 10 at 309F would have to be increased in size about 45% in order to maintain the desired emission level stipulated above. If it is feasible to reduce the gas temperature to about 250F, the size increase required would only be 17%. On the other hand with fine limestone injection, the size increases at 309 and 250F would be 225 and 56% respectively.

For the grassroots plant, the evaluation shows a cold precipitator (250F) as the best option on a cost basis.

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SUMMARY

The Environmental Protection Agency is sponsoring a variety of programs to develop technically feasible and economic means for removing sulfur oxides from stack gases of fossil fuel-fired boilers. One such means is the injection of dry limestone into the hot zone of the boiler where the gaseous sulfur oxides react with the finely dispersed additive to form solid sulfur-additive compounds which can be removed from the flue gas in mechanical and/or electrostatic precipitator collectors.

This report presents the results obtained from 37 test runs on a full-scale plant firing pulverized coal and having a dry additive injection system. The major variables studied include flue gas temperature into the dust collecting equipment, coal sulfur, and additive stoichiometry and particle size. Two levels of each variable were investigated. These tests and data from other pertinent sources have been analyzed and correlated. The results are summarized as follows:

1. The performance of the mechanical collector was relatively insensitive to all test conditions of injection or non-injection ranging between 50 and 60% efficiency. On the other hand, the overall efficiency of the dust collection system varied broadly between 72 and 99% depending significantly on the electrostatic precipitator performance. Without limestone injection, flue gas temperature and volume, and coal sulfur were the critical variables while with injection, the particle size of the additive was another important parameter.

2. The precipitation rate parameter was a significant semi-logrithmic function of the corona power input density.

   $W = 0.47+0.16 \ln P_A$ (No Injection)

   $W = 0.52+0.12 \ln P_A$ (Coarse Additive Injection)

   $W = 0.46+0.14 \ln P_A$ (Fine Additive Injection)

   where,

   W = precipitation rate parameter (FPS)

   P_A = corona power input density (kilowatts/1000 ft^2 of collecting surface)

   In general, the precipitator performance was poorer with limestone injection because the maximum corona input power density attainable was lower, particularly when fine limestone was injected.

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3. A correlation of use in sizing electrostatic precipitators was found by examining the effects of the parameters of limestone particle size, flue gas temperature, coal sulfur and limestone injection rate on corona power input density. The correlation resulted in the following equations:

   (coarse)

   $$P_A = -1.435 - 0.336S + \frac{10.0}{L} + \frac{3.87}{T}$$

   (fine)

   $$P_A = -0.990 + 0.199S - \frac{0.694}{L} + \frac{2.74}{T}$$

   where,

   S = coal sulfur fired (tons/hr)
   L = limestone injected (tons/hr)
   T = flue gas temperature ($^\circ F \times 10^{-2}$)

   By use of these equations and the correlation between precipitation rate parameter and power density shown above, it is possible to size a precipitator for the following limiting conditions:

   Coal Sulfur Fired (S)
      1.0 to 3.2 tons/hr
   Limestone Feedrate (L)
      5.3 to 16.7 tons/hr.
   Flue Gas Temperature (T)
      (240 to 315) (10^{-2}) °F.
   Stoichiometry 0.28 (L/S) = 1.0 to 4.0

4. Mechanical collector fractional efficiency curves for fly ash alone and fly ash plus additive reaction products were essentially the same ranging from 25% on the 5 micron size to 90 to 95% on the greater than 25 micron size. However, the electrostatic precipitator fractional efficiency curve on fly ash alone was nearly constant over the entire particle size range, i.e., 80 to 90%. With limestone injection, the electrostatic precipitator showed decreasing collection efficiency as particle size increased. The fly ash alone had an average mean size by weight of 19 microns at the mechanical collector inlet while with both coarse and fine limestone injection, the mean size was about 9 microns.

   The average particulate loading at the mechanical outlet-precipitator inlet varied linearly with limestone injection rate ranging from 1.5 grains per scf at 0 feedrate to about 4.0 grains at 16 tons/hr.

5. Laboratory particle resistivity measurements, in general, were higher than in-situ resistivities on samples from the same test both with and without limestone injection.

   The criticality of coal sulfur and moisture on particle resistivity was verified by in-situ measurements without limestone injection, particularly at the lower gas temperatures.

   With limestone injection, the effect of sulfur appeared to be random, but moisture conditioning at lower temperatures was still evident.

6. The precipitation rate parameter degradation as a function of particle resistivity was demonstrated. However, the critical range of resistivity seemed to be occurring in the 10^{11} to 10^{13} ohm-cm range which is somewhat higher than normal.

7. There was no obvious correlation between the chemical composition of the particulate and the performance of the precipitator.

8. An optical sensor installed on the precipitator outlet duct provided a good qualitative indication of boiler and dust collecting equipment operation. There appeared to be a linear relationship between outlet particulate loading and sensor output voltage. However, the necessity for maintaining clean lenses was evident.

9. Using a baseline of 412 pounds emitted/hr and 570,000 cfm of flue gas at 309F, estimated costs of the fly ash only electrostatic precipitator (installed) at 309F was compared with one at 600F. In addition, size modifications and costs for electrostatic precipitators with coarse and fine limestone injection (2 x stoichiometry) were compared at 250, 309, and 600F.

   The following summarizes the results:

Electrostatic Precipitator Cost and Size Factors			250F	309F	600F
Cost Installed		($/Kilowatt)			
	No	Injection	-	2.21	5.85
	Coarse	Injection	2.58	3.21	7.10
	Fine	Injection	3.44	7.20	7.10
Size Factor		(x no injection at 309F = 1.0)			
	No	Injection	-	1.0	2.44
	Coarse	Injection	1.17	1.45	2.96
	Fine	Injection	1.56	3.25	2.96

Coarse limestone at a flue gas temperature around 250F emerged as the best alternative for the limestone injection cases when only considering precipitator size modification.

However, the present Shawnee boiler flue gas is about 300F and would require cooling in order to take advantage of the 250F result. This added cost could offset the difference between coarse limestone at 309F at $3.21/kW and $2.59/kW at 250F. With fine limestone injection, the precipitator size requirements at 250F are still at a minimum but as above, extra cost for gas cooling would be required. The requirements at 309F and 600F are for all practical purposes equivalent.

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I. INTRODUCTION

This report is submitted as a partial fulfillment of the requirements for Environmental Protection Agency (EPA) Contract CPA 22-69-139 and presents the results of a full-scale study to quantify the operation of a combination mechanical collector electrostatic precipitator dust collection system with and without dry limestone injection. This study is part of the overall program being undertaken at the Shawnee power generating station of the Tennessee Valley Authority for the control of sulfur oxide emissions from a full-scale utility boiler. Definition of the effects of dry additive injection on the particulate control equipment operation and the recommended system modifications, including cost benefit data to maintain stack particulate emissions with injection equivalent to that of 2.7% sulfur and 10% ash coal-firing without injection are the primary requirements of this study. A further requirement is to recommend investigative programs to be considered for future study.

Two test campaigns were conducted by Cottrell Environmental Systems, Inc., during this study:

> The first occurred in December 1969 and related to the quantification of the dust collection system performance without additive injection. The main purpose of the data acquisition was for use as a baseline in defining the effects of subsequent additive injection;
>
> The second was in July 1971 during limestone injection and consisted of controlling four parameters at two levels which included two boiler variables (coal sulfur and flue gas temperature), and two limestone injection variables (amount and particle size).

The data and samples from these tests and other pertinent sources,[1-5]* i.e. Tennessee Valley Authority, Southern Research Institute, Research-Cottrell, Inc., Babcock and Wilcox, Co., and Dr. K. L. McLean, EPA visiting associate from Wollongong University, Australia, have been analyzed and correlated. The results are contained in subsequent sections of this report.

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*The numbers in superscript refer to the bibliography at the end of the text.

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II. TECHNICAL APPROACH

Because of the chemical and physical properties of the injected additive material, the characteristics as well as the quantity of particulate to be collected will vary substantially. These variations, including the degree of effect on the operating parameters of the dust collection system, must be monitored and evaluated in order to size and cost the system. The changes in particulate loading, specific gravity and particle size distribution will affect the performance of the mechanical collectors which precede the electrostatic precipitator. This in turn will vary the quantity and nature of the dust entering the precipitator, resulting in operational changes. Of particular significance will be the change in the electrical conductivity of the dust caused mainly by the removal of sulfur trioxide from the flue gas by the alkaline additive and the higher bulk resistance of limestone.

In the collection of fly ash-limestone reaction products by an electrostatic precipitator, the most critical parameter is the bulk electrical resistivity of the particulate. Values above 10^{10} to 10^{11} ohm-cm result in reduced electrical power to the precipitator and poor performance. This particular subject has been treated extensively in the literature[6-9] and will be covered in more detail in subsequent sections of this report. A comparison of present results with past experience will also be discussed.

The main operational parameters that were monitored during the test program include:

1. Particulate Characteristics (Fly ash, Fly ash-Limestone Reaction Products)
    (a) Specific Gravity
    (b) Particle Size Analysis (Bahco and Sieve)
    (c) Bulk Electrical Resistivity (Laboratory)
    (d) In-Situ Electrical Resistivity
    (e) Chemical Analysis
        (1) Loss on Ignition
        (2) SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, TiO_2 Na_2O, K_2O, SO_4=, SO_3=, S=

2. Collector Variables
    (a) Particulate Loadings Inlet and Outlet (ESP and MC)
    (b) Pressure Drop of Mechanical Collector
    (c) Current-Voltage Characteristics of ESP
    (d) Sparking Rate of ESP
    (e) Particulate Collection Efficiency (ESP and MC)

3. Boiler Variables
    (a) Flue Gas Analysis (O_2, SO_2, H_2O)
    (b) MW Load, Steam, Air
    (c) Flue Gas Temperature, Pressure

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- (d) Gas Volume
- (e) Coal-Firing Rate
- (f) Limestone Addition Rate

4. Additive Characteristics
   - (a) Particle Size Analysis (Bahco and Sieve)
   - (b) Electrical Resistivity (Laboratory)
   - (c) Chemical Analysis
     - (1) CaO, MgO, Fe_2O_3, SiO_2

5. Coal Analysis (a)
   - (a) Sulfur
     - (1) Pyritic
     - (2) Organic
     - (3) Sulfate
   - (b) Ash
   - (c) Moisture

The objective of the test program is to provide an assessment of the particulate collecting system with and without additives for use in establishing the additional gas cleaning equipment required to maintain stack emissions at levels associated with 2.7% sulfur, 10% ash, coal-firing. In addition, other alternatives such as gas cooling, hot precipitator, gas conditioning, and type of electrical energization will be evaluated.

III. TEST METHODS

The test methods used were in compliance with the ASME-PTC 27 and ASME-PTC 28 with regard to determining gas volume, particulate loading and analyzing the collected material.

1. Gas Velocity Measurements are required to obtain the necessary data for determining:
   - (a) Total gas volume being treated by the dust collector.
   - (b) Distribution and flow pattern of gas entering the collector.
   - (c) The sampling rates required to obtain representative particulate loadings entering and leaving the collector.

The equipment used to make these measurements during the test program reported herein is shown schematically in Figure 1(a). It consisted of a Stauscheibe pitot tube with inclined draft gauge for velocity head readings, plus a thermocouple and potentiometer for simultaneous temperature measurements.

The gas velocity was calculated from the equation:

$$v = 15.6\, k_p \left[\frac{T_D h}{P}\right]^{1/2} = 13.37 \left[\frac{T_D h}{P}\right]^{1/2} \qquad (1)$$

Where,

v = Gas Velocity - FPS
T_D = Duct Temp. °F + 460° - R
h = Velocity Head - "H_2O
P = Duct Pressure - "Hg
= Barometric pressure $\pm \dfrac{\text{Duct Static Pressure ("}H_2O\text{)}}{13.6}$
k_p = 0.855 = Stauscheibe pitot tube factor
15.6 = Constant for flue gas from pulverized coal combustion

The total gas volume was calculated from the equation:

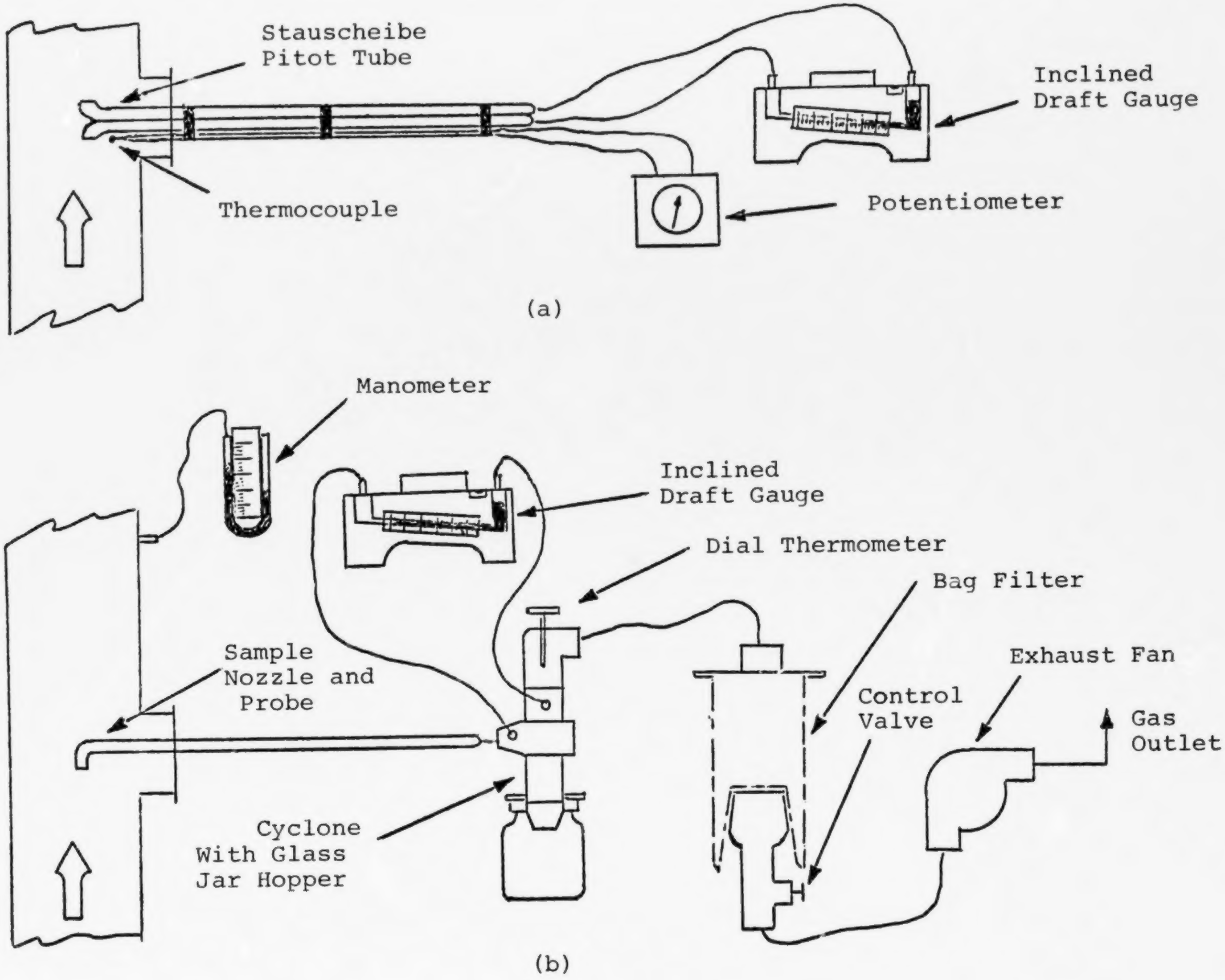
$$V = 60 A\bar{v} \qquad (2)$$

Where,

V = Total Gas Volume - ACFM
A = Flue Cross-Sectional Area Where Velocity Traverse Made - Ft^2
$\bar{v}$ = Average gas velocity obtained from traverse - FPS
60 = seconds/minute

FIGURE 1

EQUIPMENT FOR MAKING GAS VELOCITY MEASUREMENTS AND TAKING PARTICULATE SAMPLES



2. Moisture Content of the gas was determined by hot-gas psychrometry which involves determining the wet and dry bulb temperatures of the gas. The following equations are used to calculate the moisture content:

$$e = e^1 - 0.01\ (t_d - t_w), \text{ and} \tag{3}$$

$$M = \left(\frac{e}{B \pm S_f}\right)\left(100\right) \tag{4}$$

Where,

e = Vapor pressure of gas - "Hg
e^1 = Vapor pressure of saturated gas at t_w - "Hg
t_d = Dry bulb temperature - °F
t_w = Wet bulb temperature - °F
M = Moisture in gas - %
B = Barometric pressure - "Hg
S_f = Flue pressure - "Hg

3. Particulate Sampling was done by means of the large volume Aerotec sampling equipment which is shown schematically in Figure 1(b). The equipment consists of a sample nozzle and probe connected to the dust separating elements which include a high efficiency cyclone with a glass jar hopper and a filter bag (both predried and weighed) followed by a fan for drawing the gas through the sampling train. The gas flow rate is monitored by measuring the pressure drop across the calibrated cyclone and can be varied to maintain isokinetic sampling by means of a valve located at the filter bag outlet. The gas temperature is measured at the cyclone outlet with a dial thermometer and the gas pressure is assumed to be the same as the main duct pressure which is determined by barometer and a static pressure measurement.

The total cubic feet of gas sampled was calculated from the equations:

$$V_p = 3930\ A_n\ k_p \left(\frac{T_s\ hp}{T_D}\right)^{1/2} \tag{5}$$

$$V_t = \Sigma_O^N \quad V_p\text{'s} \tag{6}$$

$$V_S = \left(\frac{530B}{30}\right)\left(V_t\right)\left(\frac{1}{T_s}\right)^{1/2} \quad t \tag{7}$$

Where,

V_p = Volume sample rate at each traverse point - CFM
A_n = Sample nozzle area - Ft^2

k_p = 0.855 = Stauscheibe pitot tube factor

T_S = Sample train temperature - °R

T_D = Duct temperature - °R

h_p = Velocity head at each sample point - "H_2O

V_t = Total volume sample rate - CFM

N = Number of sample points

V_S = Total volume sampled - Ft^3 @ 70 F and 30" Hg

B = Barometric pressure - "Hg

t = Sampling time at each point - minutes

3930 = Calibration constant of cyclone orifice

The amount of particulate collected was determined by drying and reweighing the cyclone sampler jar and filter bag. The particulate loading was calculated using the equation:

$$D = \frac{(D_C)(15.43)}{V_S} \qquad (8)$$

Where,

D = Particulate loading - grains/Ft^3 @ 70 F and 30 "Hg

D_C = Net weight of particulate collected - grams

V_S = Total volume sampled - Ft^3 @ 70 F and 30 "Hg

15.43 = Conversion factor, grams to grains

The efficiency of the collector was determined by the equation:

$$E = \left(\frac{D_I - D_O}{D_I}\right)\left(100\right) \qquad (9)$$

Where,

E = Efficiency - %

D_I = Inlet particulate loading - grains/Ft^3

D_O = Outlet particulate loading - grains/Ft^3

4. Test Sections were located in areas of reasonably straight runs of duct work and free of interference from nearby equipment. Figure 2 is a schematic diagram of the boiler, collectors, and associated equipment showing the location of the sampling areas. Figures 3 through 5 detail the actual dimensions and number of sample points used at the mechanical collector inlet and the electrostatic precipitator inlet and outlet.

5. In-Situ Resistivity measurements were made using a portable apparatus (Figure 6) designed and supplied by Research-Cottrell, Inc. The apparatus measures the electrical

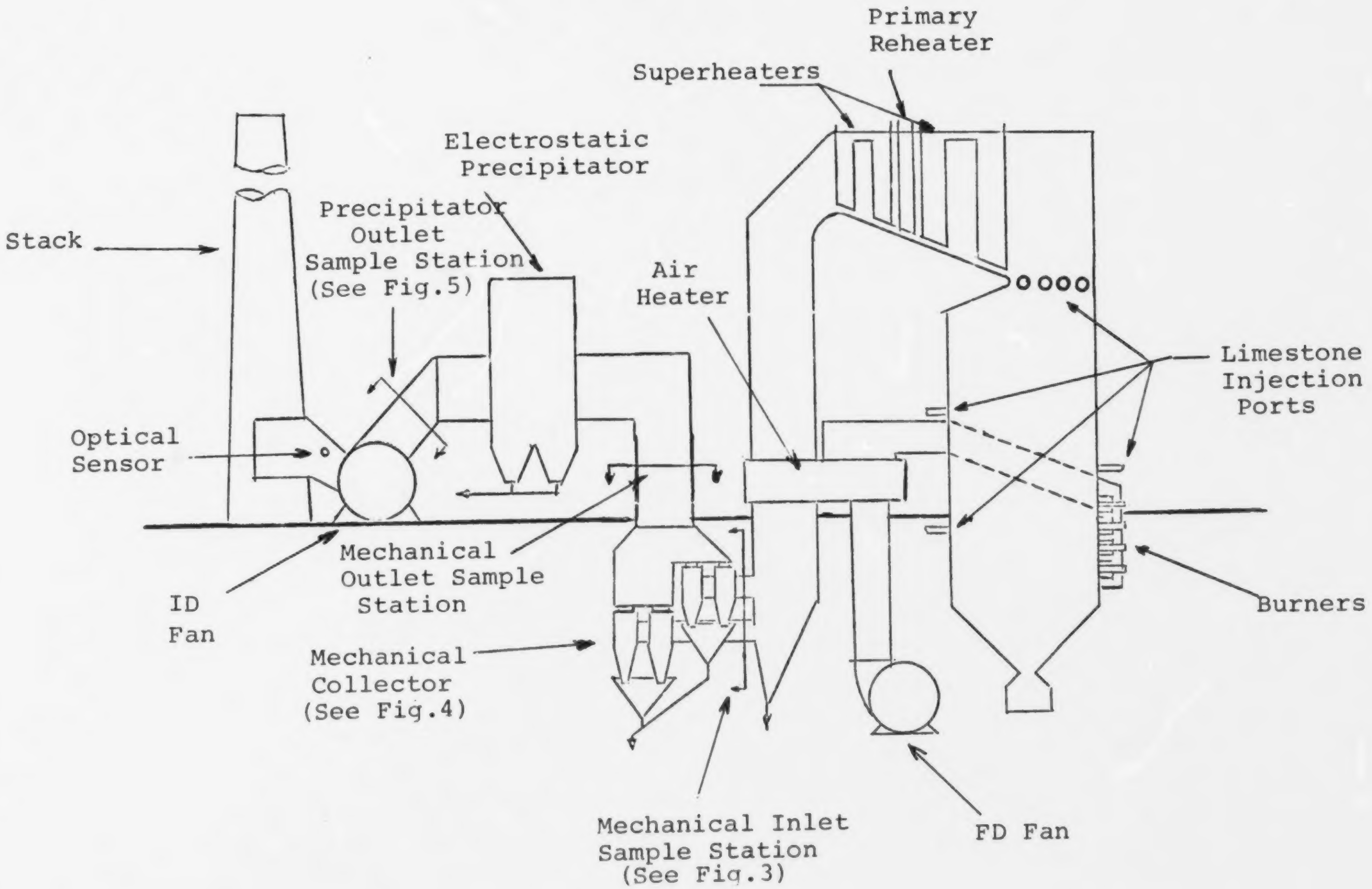


FIGURE 2

SCHEMATIC DIAGRAM OF BOILER #10 SHAWNEE STATION, TVA

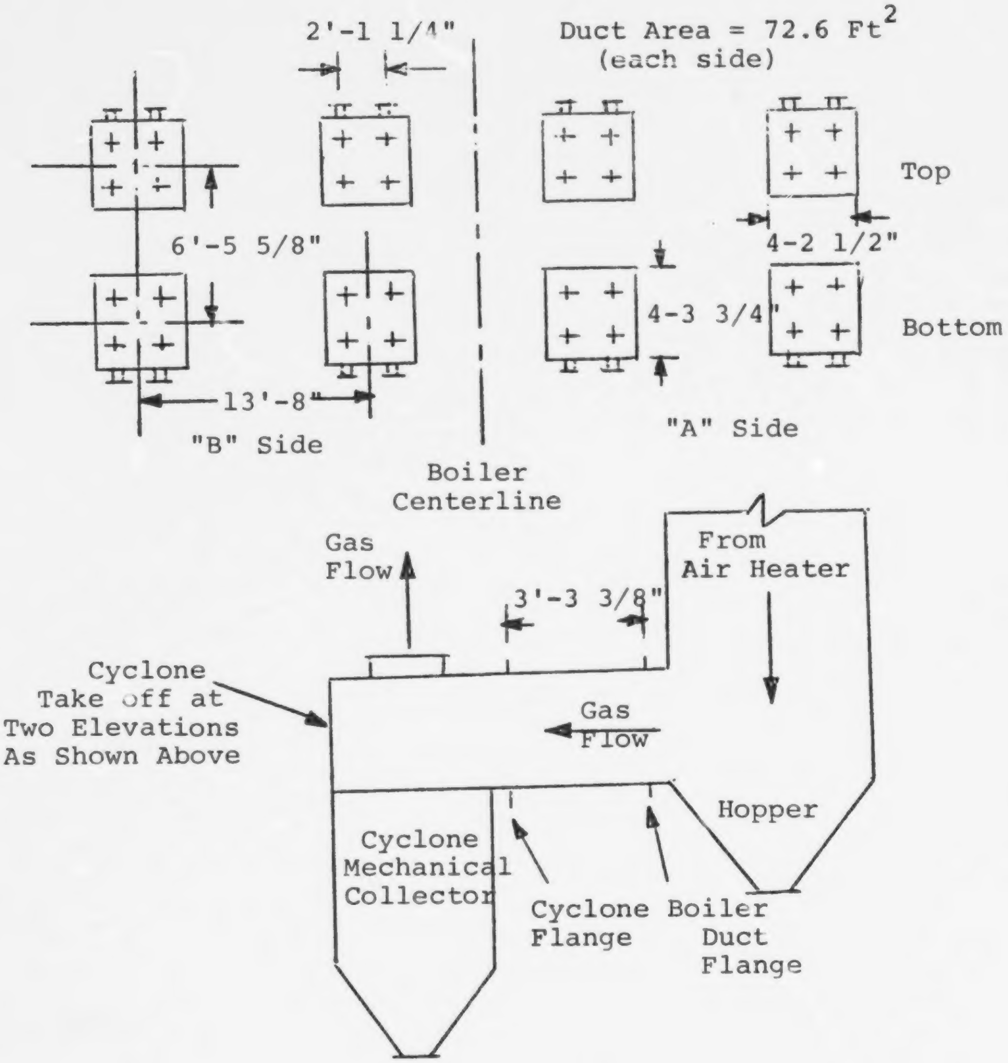


FIGURE 3

DETAILS OF MECHANICAL COLLECTOR

INLET SAMPLING STATION

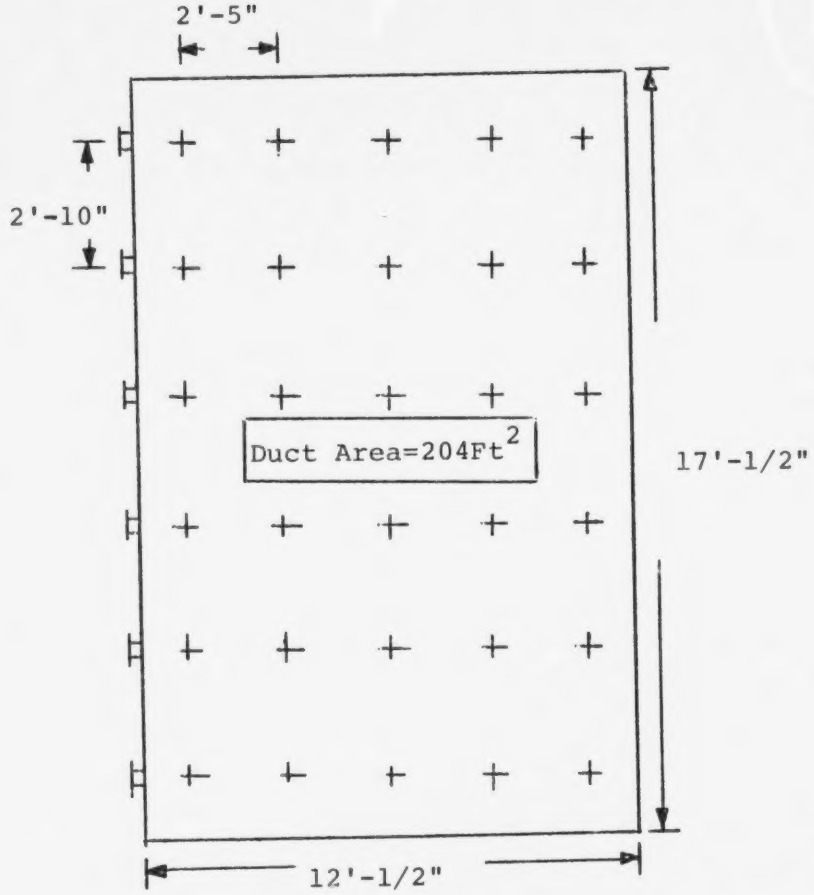


FIGURE 4

DETAILS OF MECHANICAL COLLECTOR
OUTLET - ELECTROSTATIC PRECIPITATOR INLET
SAMPLING STATION

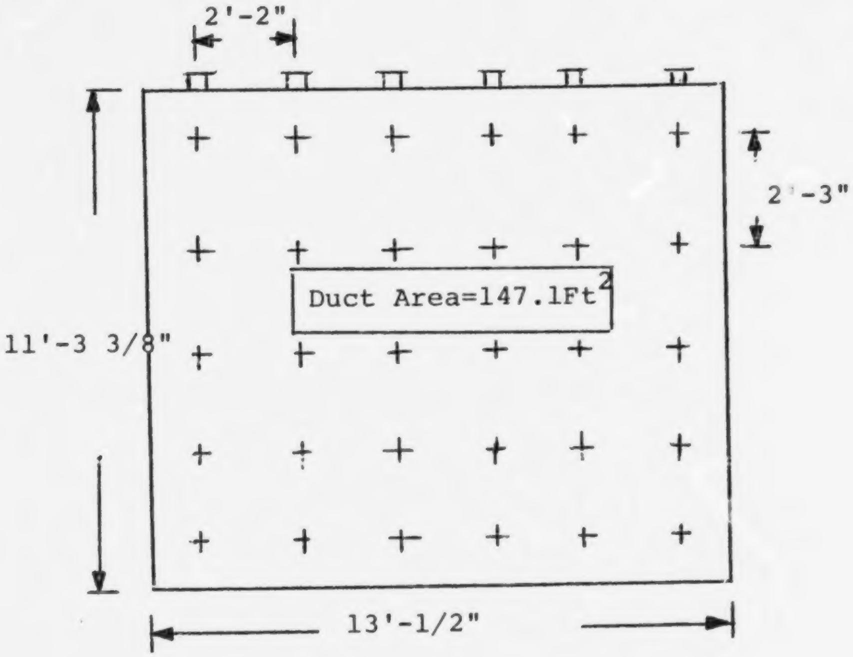
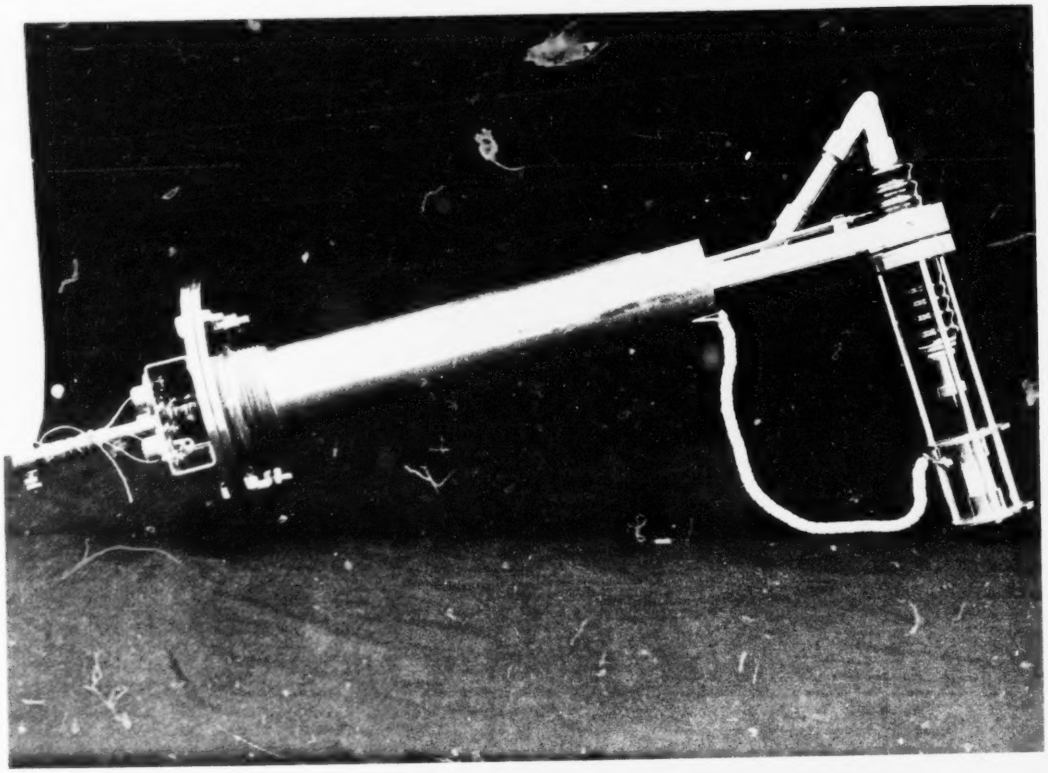
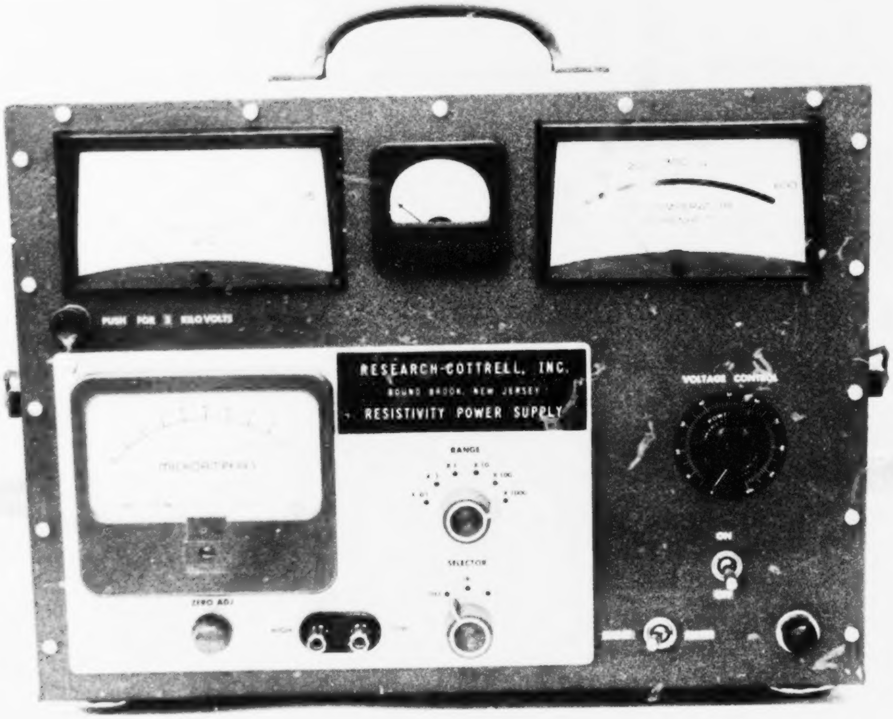


FIGURE 5
DETAILS OF ELECTROSTATIC
PRECIPITATOR OUTLET SAMPLING STATION

FIGURE 6 - IN-SITU RESISTIVITY APPARATUS



POWER SUPPLY AND METERING UNIT



resistance of a layer of dust precipitated from flue gas under actual operating conditions. It consists of a small electrostatic point-plane precipitator (Figure 7), an iron constantan thermocouple located near the plane, and a control unit for supplying power and measuring voltage and current.

6. The Laboratory Resistivity measurements were made in apparatus shown photographically and schematically in Figures 8 and 9. The cell shown in Figure 10 is mounted in an electrically heated and thermostatically controlled chamber capable of reaching temperatures in the 650° F range. In addition, humidity can be controlled from bone dry up to 30 or 40% by volume. The schematic electrical circuitry is shown in Figure 11.

7. The skeletal or true density of the particulate samples was determined by the pycnometer method. Approximately a 5-gram sample is transferred to a weighed pycnometer bottle of known volume and reweighed. The bottle is half filled with a suitable liquid (selected on the basis of dust solubility being a minimum) and placed in a dessicator-type container which can be evacuated (see Figure 12). After all air has been removed from the dust sample, the pycnometer bottle is filled to capacity, thermally equilibrated and reweighed. The dust density is calculated as follows:

$$V_1 = \frac{W_3 - W_2}{d_1} \qquad (10)$$

$$d_p = \frac{W_2 - W_1}{V_p - V_1} \qquad (11)$$

Where,

W = Weight of pycnometer bottle - grams
W_2 = Weight of pycnometer + dust - grams
W_3 = Weight of pycnometer + dust + liquid - grams
V_1 = Volume of liquid - cubic centimeters
V_p = Volume of pycnometer - cubic centimeters
d_1 = Density of liquid - grams/cubic centimeters
d_p = True density of dust - grams/cubic centimeters

8. The particle size distributions were made by sieve and Bahco methods. A set of 3 inch U.S. Standard sieves and pan are weighed. The sieves are then nested reading 50-mesh (297 microns), 100-mesh (149 microns), 200-mesh (74 microns), 325-mesh (44 microns) and pan from top to bottom. About a 2 gram sample of dried dust is placed on the top sieve and covered. The set of sieves is then placed in a Ro-tap and shaken for twenty minutes. The sieves are brushed lightly and reweighed. The weight of fractions is obtained by difference and final results are calculated as "percent fraction separated" and reported as "cumulative percent finer."

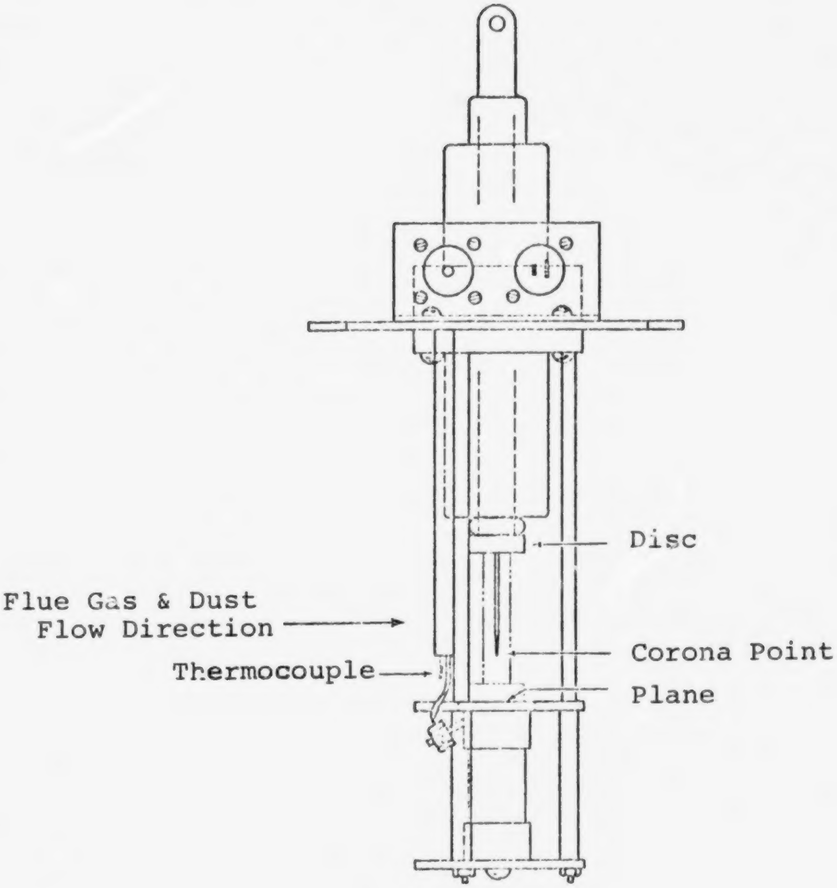


FIGURE 7

POINT-PLANE RESISTIVITY CELL

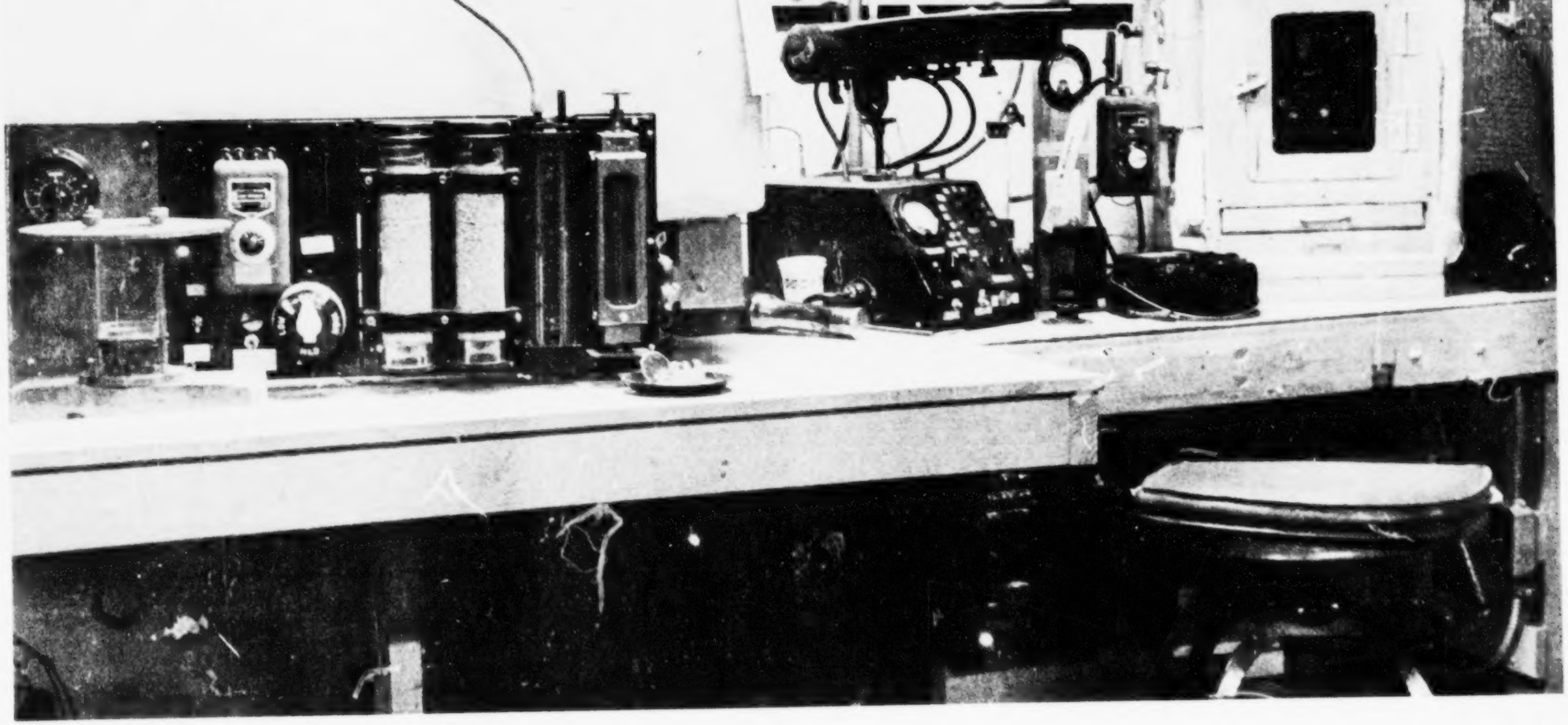


FIGURE 8 - LABORATORY RESISTIVITY MEASURING APPARATUS

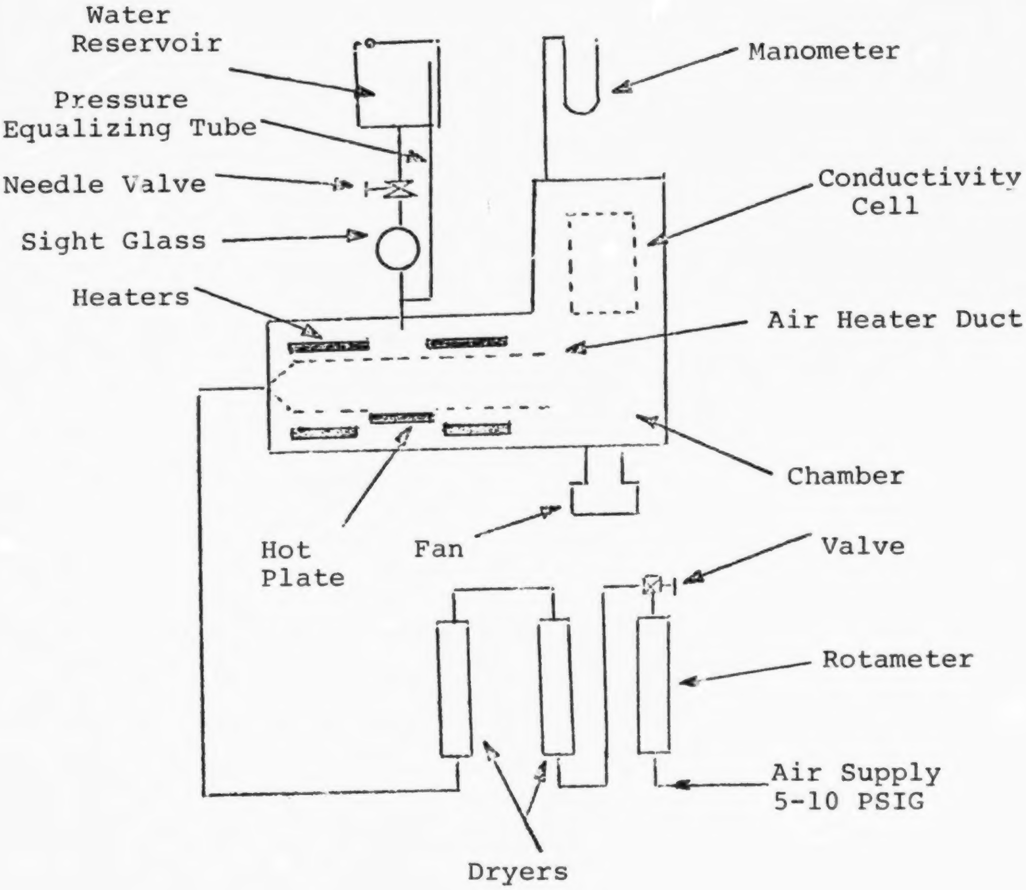


FIGURE 9

SCHEMATIC DIAGRAM OF LABORATORY
RESISTIVITY MEASURING APPARATUS

FIGURE 10

CROSS-SECTION DIAGRAM OF MEASURING CELL USED IN LABORATORY RESISTIVITY APPARATUS

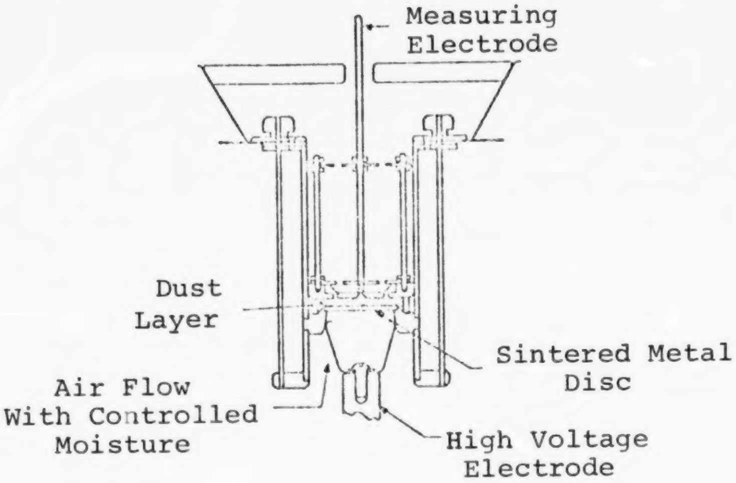
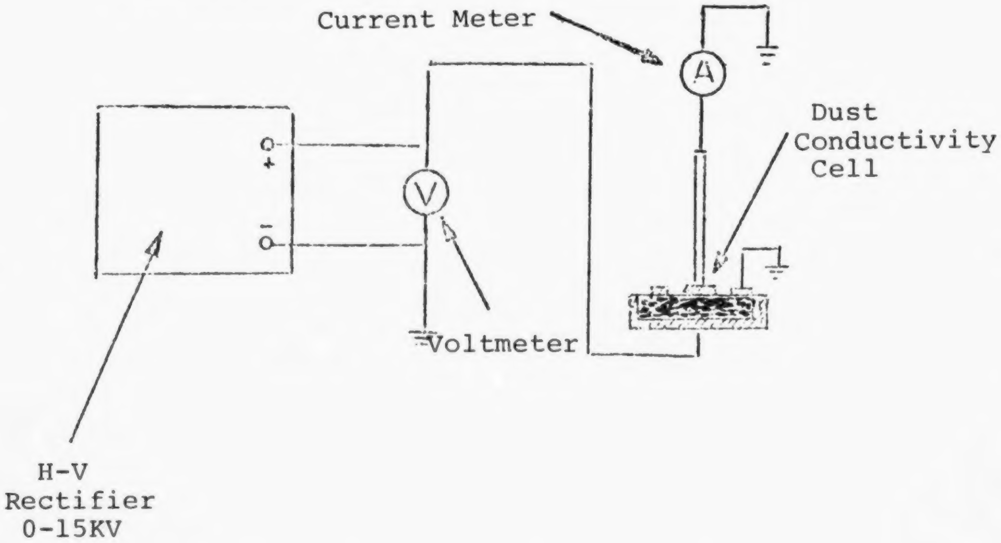


FIGURE 11

SCHEMATIC OF ELECTRIC CIRCUIT FOR LABORATORY RESISTIVITY APPARATUS



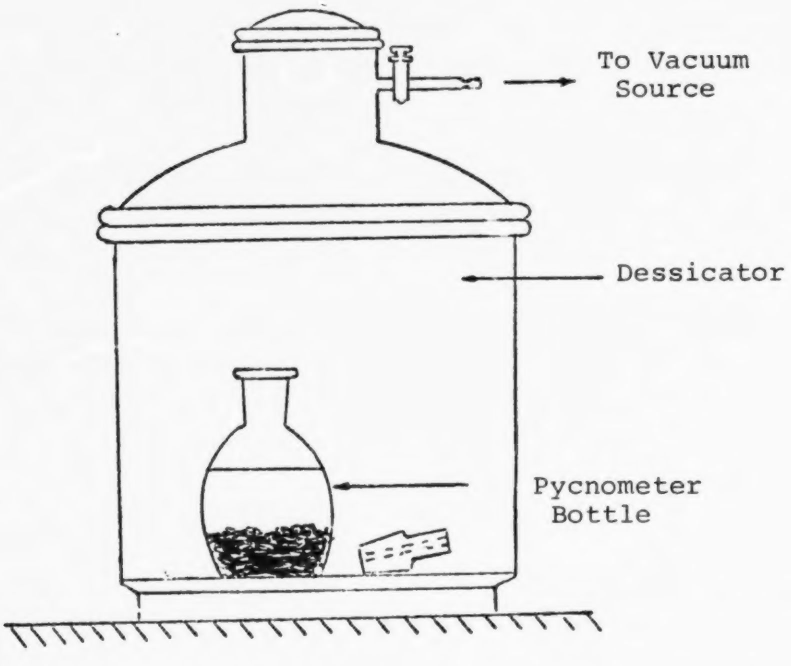


FIGURE 12

APPARATUS FOR MEASURING SKELETAL
OR TRUE DENSITY OF PARTICULATE

The Bahco method of sub-sieve particle sizing uses a centrifugal classifier (see Figure 13) which operates at 3500 RPM. The sample is introduced into a spiral-shaped air current flowing toward the center. Depending on the size, weight and shape of the particles, a certain fraction is accelerated by centrifugal force toward the periphery of the whirl, while the remainder is carried toward the center. By varying flow through the use of throttles, the dust sample can be divided into a number of fractions between about 2 and 30 microns. This particular method is not absolute but must be calibrated with a standard sample of known distribution based on an absolute method.

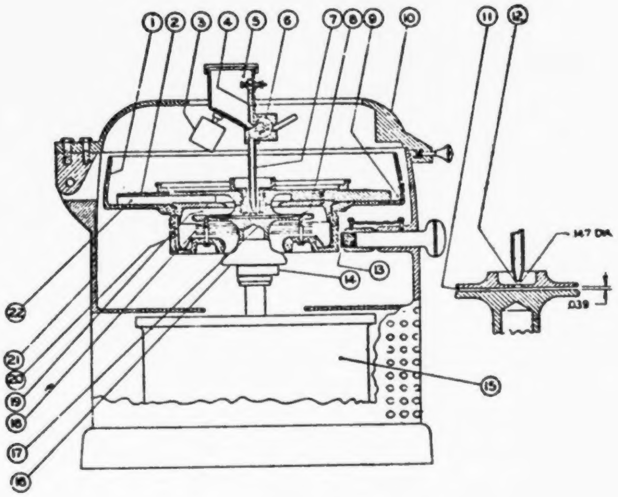
9. The stack opacity was monitored by means of an optical sensor designed and supplied by Research-Cottrell, Inc. A schematic diagram of the system is shown in Figure 14. A light source and optical sensor are contained in sealed housings mounted on opposite sides of a duct. Sufficient sensitivity and flexibility are provided to permit full scale recorder calibration corresponding to 20 up to 100% optical obscuration for aerosol paths ranging from 6 to 30 feet. (20% is a No. 1 Ringelmann and 100% a No. 5 Ringelmann). Normally, a 0-5 Ringelmann scale calibration is used to encompass peak emission periods such as sootblowing.

   A clean gas reference signal is continually compared with the dirty gas signal by means of a differential signal amplifier whose signal is recorded continually as optical density readout.

10. Coal Analyses were provided by Smith, Rudy and Company, chemists in Philadelphia, Pennsylvania, while other chemical analyses of particulate samples were performed by the TVA laboratory chemists located in Chattanooga, Tennesseee.

FIGURE 13

BAHCO CENTRIFUGAL PARTICLE CLASSIFIER



1 Rotor Casting
2 Fan
3 Vibrator
4 Adjustable Slide
5 Feed Hopper
6 Revolving Brush
7 Feed Tube
8 Feed Slot
9 Fan Wheel Outlet
10 Cover
11 Rotary Duct
12 Feed Hole
13 Brake
14 Throttle Spacer
15 Motor - 3520 RPM
16 Grading Member
17 Threaded Spindle
18 Symmetrical Disc
19 Sifting Chamber
20 Catch Basin
21 Housing
22 Radial Vanes

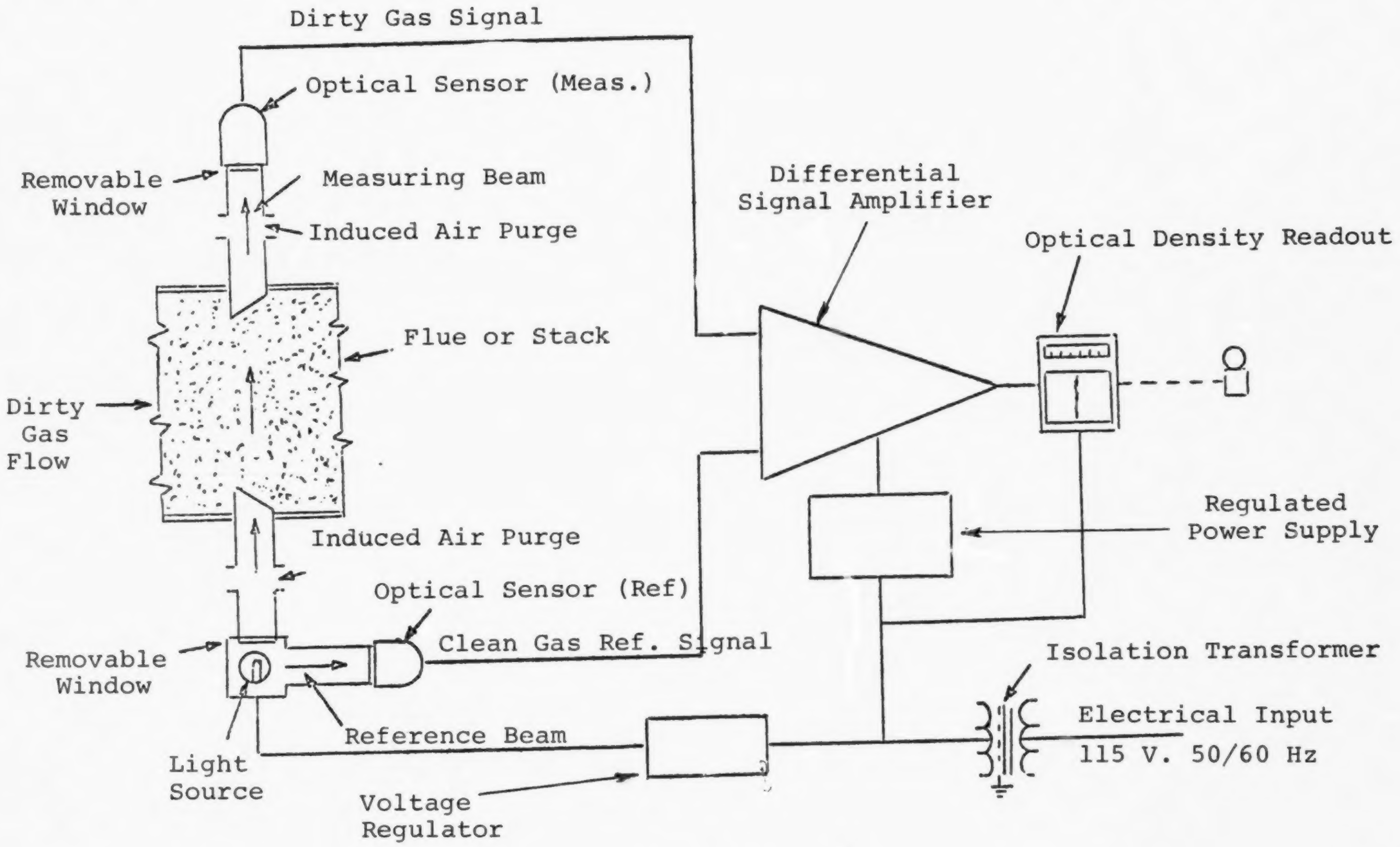


FIGURE 14

FUNCTIONAL DIAGRAM OF THE OPTICAL SENSOR

IV. TEST CONDITIONS AND PROCEDURES

The initial test campaign without additive injection was conducted with a boiler generated load of about 140 megawatts with very little variation. No attempt was made to control the coal sulfur. Soot-blowing was curtailed during the tests. Mechanical and electrical precipitator hoppers were emptied at the beginning and end of each test period at which time samples were taken. This procedure ensured representative hopper samples. Both "A" and "B" precipitators of boiler No. 10 were tested during this campaign. (See Figure 15 for schematic diagram of electrostatic precipitator). Coal feed rates and samples were obtained by monitoring and grab-sampling the coal feeders. Boiler conditions were recorded from the control room panels.

Main operating difficulties were encountered with the electrostatic precipitators in the form of short circuits caused by broken discharge electrodes.

The second test series was conducted with and without additive injection. Boiler generated load was difficult to control because of external conditions of low water level in the river supplying the condensers. As a result, load varied from 125 MW to 148 MW during the test period.

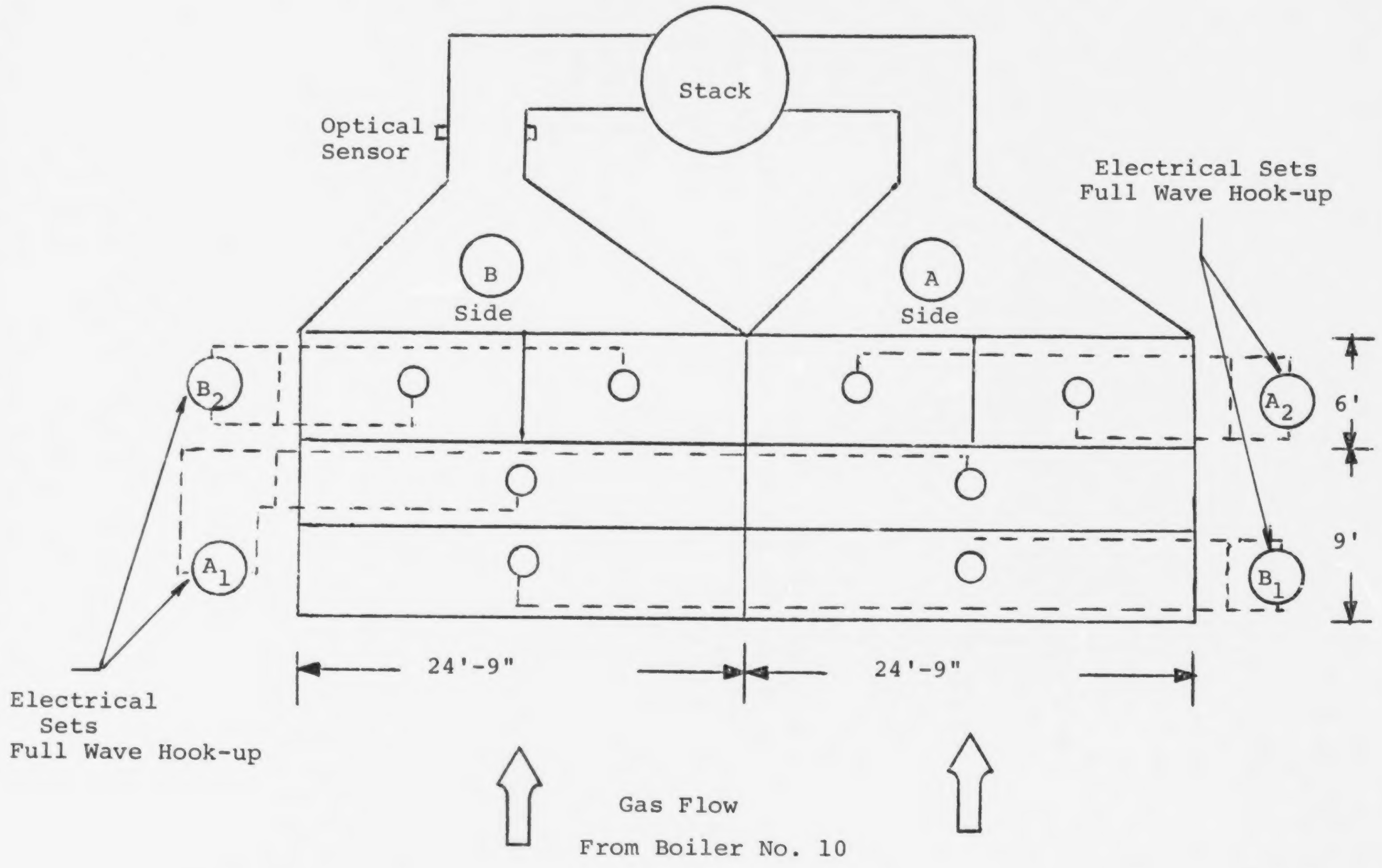
Extreme ambient temperature conditions at the mechanical collector inlet sampling station (160-180 F.) caused equipment failure and hampered the sampling personnel. The sampling equipment was revised by inserting a flexible hose between the sampling probe and the Aerotec Sampler. This allowed placement of the sampler in a somewhat cooler location.

The limestone feeder tripped-off at high feed rates. This was finally resolved by air-cooling the feeder motor. The electrostatic precipitator transformer-rectifier controls were erratic in operation. The silicon controlled rectifier firing circuit was too sensitive to sparking which caused the precipitator voltage to be lower at the first occurrence of sparking rather than at an optimum rate. The problem was solved by replacing faulty resistors in the control circuit.

As shown in Figure 15, the "A" and "B" side of the electrostatic precipitator are electrically interconnected. For the tests where temperature on the "B" side was reduced to about 250 F. by fan biasing, the "A" side gas temperature would rise to over 350 F. This meant that the "A" side dust resistivity could influence the operation of the "B" side portion of the electrostatic precipitator. This interference was corrected by deenergizing the "A" side and using the electrical sets to energize only the "B" side.

FIGURE 15

SCHEMATIC DIAGRAM OF ELECTROSTATIC PRECIPITATOR ARRANGEMENT AND ELECTRICAL HOOK-UP



Soot blowing, condenser repairs, and hopper emptying took more time than originally anticipated and modifications in test and operating procedures were instituted. In order to complete as much of the statistically designed test program as possible within reasonable cost and schedule constraints, the following changes in procedure were agreed upon:

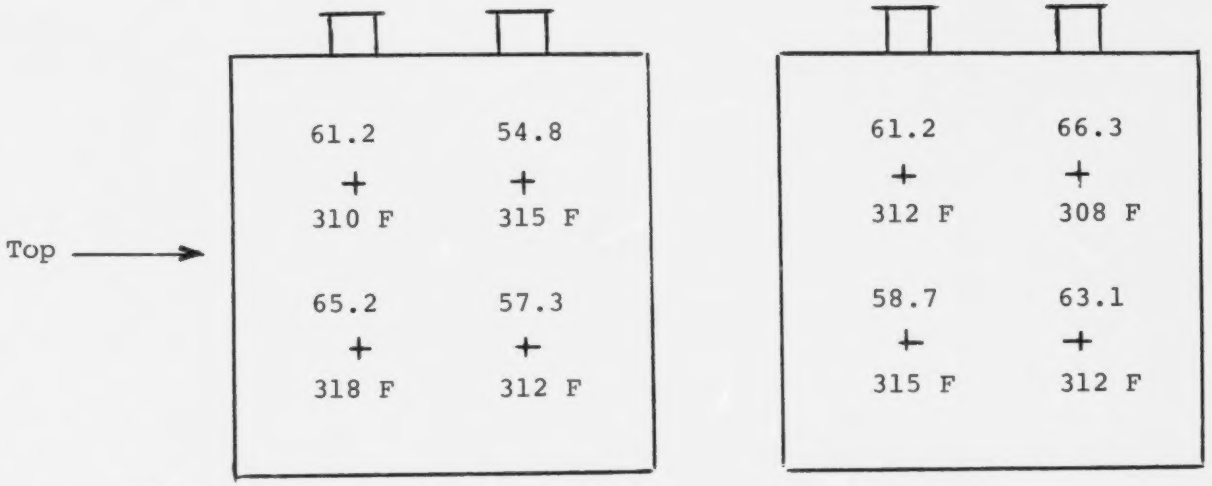
1. The velocity and temperature traverses before each test were eliminated. The gas temperature and pressure drop of the mechanical collector were adjusted by fan biasing to give the desired test conditions at the electrostatic precipitator inlet. Previous velocity and temperature traverses at similar mechanical collector conditions (temperature within 5° F and pressure drop within 10%) were then used to obtain isokinetic sampling. Figures 16 to 18 are representative temperature and velocity traverses for the three sampling stations.

2. Elimination of sampling at the mechanical inlet for most tests allowed the use of these two samplers, one each, on the ESP inlet and outlet or a total of three samplers at each of these locations. Time per test was thus reduced to 50 minutes from 75 minutes thereby improving test scheduling without reducing the amount of dust collected.

Tables I and II list the completed tests for both campaigns.

FIGURE 16

REPRESENTATIVE TEMPERATURE AND VELOCITY TRAVERSE AT THE MECHANICAL COLLECTOR INLET ("B" SIDE)



Avg. Velocity = 60.4 FPS
Avg. Temperature =
ACFM of Gas = (60.4)(72.6)(60) = 263,157

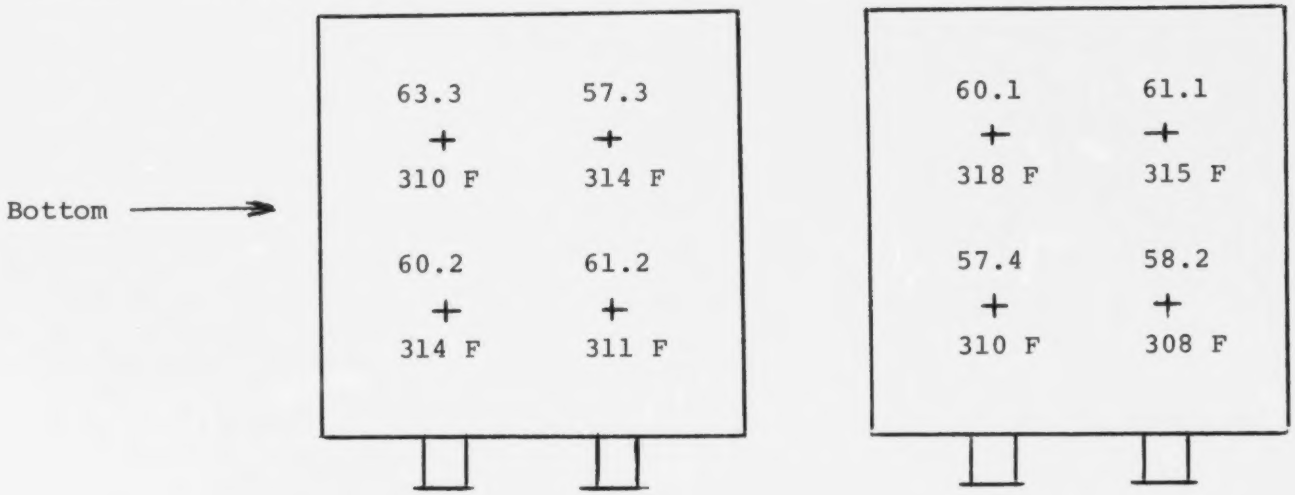
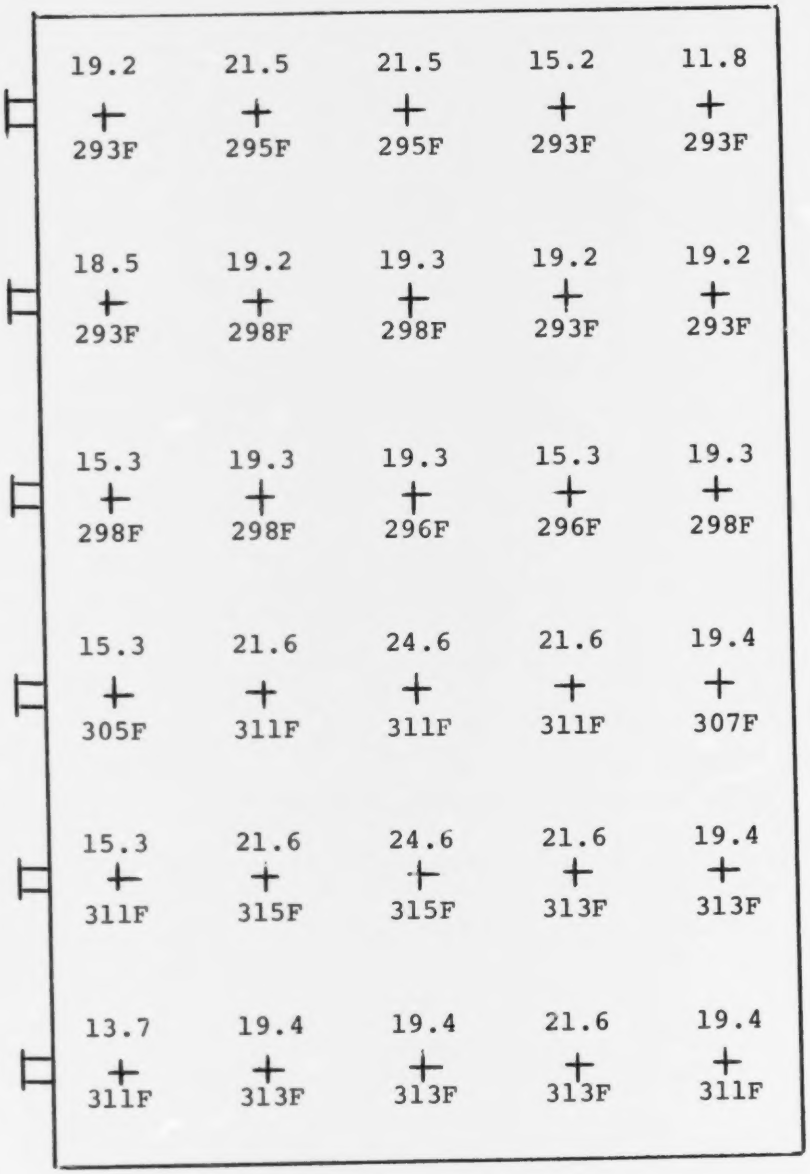


FIGURE 17

REPRESENTATIVE TEMPERATURE AND VELOCITY TRAVERSE AT THE MECHANICAL OUTLET - PRECIPITATOR INLET SAMPLE STATION ("B" SIDE)

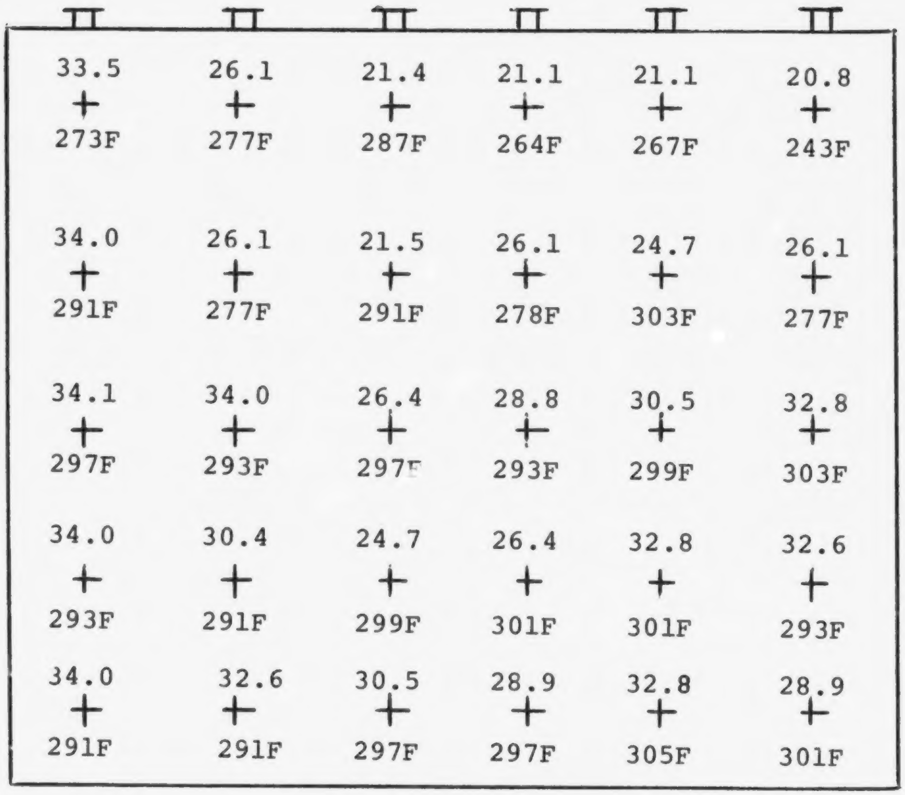


19.2 293F	21.5 295F	21.5 295F	15.2 293F	11.8 293F
18.5 293F	19.2 298F	19.3 298F	19.2 293F	19.2 293F
15.3 298F	19.3 298F	19.3 296F	15.3 296F	19.3 298F
15.3 305F	21.6 311F	24.6 311F	21.6 311F	19.4 307F
15.3 311F	21.6 315F	24.6 315F	21.6 313F	19.4 313F
13.7 311F	19.4 313F	19.4 313F	21.6 313F	19.4 311F

Avg. Velocity = 19.1 FPS
Avg. Temperature = 303F
ACFM of Gas = (19.1)(204)(60) = 233,784

FIGURE 18

REPRESENTATIVE TEMPERATURE AND VELOCITY TRAVERSE AT THE PRECIPITATOR OUTLET SAMPLING STATION ("B" SIDE)



33.5 273F	26.1 277F	21.4 287F	21.1 264F	21.1 267F	20.8 243F
34.0 291F	26.1 277F	21.5 291F	26.1 278F	24.7 303F	26.1 277F
34.1 297F	34.0 293F	26.4 297F	28.8 293F	30.5 299F	32.8 303F
34.0 293F	30.4 291F	24.7 299F	26.4 301F	32.8 301F	32.6 293F
34.0 291F	32.6 291F	30.5 297F	28.9 297F	32.8 305F	28.9 301F

Avg. Velocity = 28.6 FPS
Avg. Temperature = 289F
ACFM of Gas = (28.6)(147.1)(60) = 252,424

TABLE I

COMPLETED TESTS (FIRST CAMPAIGN)

CONTRACT CPA 22-69-139

Test Number	Additive Stoich. X_1	Gas Temp. X_2	Particle Size X_3	% S in Coal X_4	Date Performed
1A*	0	+	0	+	12/11/69
1B*	0	+	0	+	12/11
2A	0	+	0	+	12/12
3A*	0	+	0	-	12/14
3B*	0	+	0	-	12/13
4A*	0	+	0	+	12/14
4B*	0	+	0	-	12/13
5A*	0	+	0	+	12/15
5B*	0	+	0	+	12/15

KEY:

LEVEL	X_2	X_4
+	289-318	2.30-4.10
-	238-256	1.00-2.29

* Mechanical Collector Inlet Sample Taken

TABLE II

COMPLETED TESTS (SECOND CAMPAIGN)

CONTRACT CPA 22-69-139 MODIFICATIONS 6 & 7

Test Number	Additive Stoich. X_1	Gas Temp. X_2	Particle Size X_3	% S in Coal X_4	Date Performed
1	0	+	0	+	7/9/71
2*	-	+	-	+	7/10
3*	-	-	-	+	
4*	+	+	-	-	7/12
5*	-	-	-	+	
6*	+	+	-	+	7/13
8*	-	-	-	+	7/14
9	0	-	0	-	7/15
10	+	-	+	-	
11	+	+	+	-	
25	-	-	+	-	7/19
19	0	-	0	≤ 0.8	7/20
20	0	+	0	≤ 0.8	
21	0	-	0	≤ 0.8	
22	0	+	0	≤ 0.8	
23	-	+	-	≤ 0.8	
24	+	+	-	≤ 0.8	
28	-	+	-	+	7/21
29	-	-	-	+	
30	-	+	-	+	
16	0	-	0	-	7/22
17	+	-	-	-	
18	+	+	-	-	
26	-	+	-	-	7/23
27	-	-	-	-	
14*	+	+	+	+	7/24
15*	+	-	+	-	
32*	-	+	+	+	7/26
33*	-	-	+	+	

KEY:

LEVEL	X_1	X_2	X_3	X_4
+	2.0-4.0	289-318°F	COURSE (50%-400M)	2.30-4.10
-	0.5-2.0	238-256°F	FINE (80%-400M)	1.00-2.29

* Mechanical Collector Inlet Sample Taken

NOTE: All tests were run on "B" side. However, first five tests had electrical equipment energizing both "A" and "B" sides. Test six on had only "B" side energized, one set per section (fullwave).

V. TEST RESULTS AND SAMPLE ANALYSES

1. Test Data

Tables III through XV summarize the data from both the CES test programs, and the TVA test programs. All runs were made on Boiler No. 10 at Shawnee Station. However, the TVA tests were conducted on the "A" precipitator while the first CES test program was on both "A" and "B" precipitators and the second was on the "B" only. (See Figure 15.)

Since the flue gas and particulate to both "A" and "B" precipitators came from the same boiler, there is no obvious reason to expect any signficant difference in results due to the side tested, and for analysis purposes the test data can be considered comparable. The only exception is the optical sensor data which was recorded on the "B" side and a quantitative analysis requires test data from the "B" side. However, a qualitative evaluation of the data can include "A" side tests as well.

2. Coal Analyses

Tables XVI through XVIII summarize coal sample analyses for both the CES and TVA programs, and the Babcock and Wilcox pilot plant work at Alliance, Ohio.

3. Particle Size Analyses (Bahco, sieve and specific gravity)

Tables XIX through XXII summarize the Bahco and sieve analyses of samples obtained during the CES test programs. Included are limestone feed samples, fly ash samples and reacted limestone fly ash mixtures.

4. Resistivities

Tables XXIII through XXV summarize all laboratory and in-situ resistivity measurements made on samples from the CES programs. Table XXVI shows resistivities obtained on fly ash from various coals used in the Babcock and Wilcox pilot program.

5. Chemical Analyses

Tables XXVII through XXIX summarize all the chemical analyses obtained on the particulate samples from both of the CES test programs. These analyses were performed by TVA personnel at their Chattanooga, Tennessee, laboratory.

TABLE III

SUMMARY OF THE TEST DATA FROM THE COTTRELL ENVIRONMENTAL SYSTEM'S FIRST TEST SERIES

(December, 1969)

Test No.	Feed Rate Tons/Hr. Coal	Feed Rate Tons/Hr. Limestone	Bar. Press. "Hg	Duct Press. ID Fan in "H_2O	In-Situ Resistivity Pptr. Inlet Temp. °F	In-Situ Resistivity Pptr. Inlet OHM-CM	Elec. Pptr. Inlet T °F	Elec. Pptr. Gas Vol. MACFM	Elec. Pptr. Vel. FPS
1A	57.0	0	29.61	-13.90	—	—	—	275	6.2
1B	57.0	0	29.75	-13.25	—	—	—	255	5.7
2A	56.0	0	29.71	-13.60	293	4.8×10^{9}	293	275	6.2
3A	58.0	0	29.75	-13.30	318	2.1×10^{10}	318	273	6.1
3B	59.0	0	29.91	-12.75	293	2.6×10^{11}	293	237	5.3
4A	58.0	0	29.88	-13.10	312	4.7×10^{10}	312	270	6.1
4B	59.0	0	29.75	-12.75	302	3.0×10^{11}	302	230	5.2
5A	57.0	0	29.98	-13.30	—	—	—	276	6.2
5B	57.0	0	29.96	-12.75	—	—	—	230	5.2

(a)

Test No.	Unit Load	Steam M Lbs. Per Hr.	Air M Lbs. Per Hr.	Flue Gas % by Volume O_2	Flue Gas % by Volume H_2O	MC Inlet Temp. °F	ΔP "H_2O AH	ΔP "H_2O MC	ΔP "H_2O Pptr.
1A	140	970	1030	3.0-5.0	—	295	2.3	4.40	0.3
1B	140	965	1020	2.3-4.0	—	300	2.3	3.80	0.3
2A	137-144	940-1000	1000-1030	3.0-5.0	8.3	297	2.3	4.20	0.3
3A	140	960	1020	2.0-4.0	—	300	2.2	4.30	0.3
3B	140	960	1010	2.0-4.0	—	303	2.3	3.80	0.3
4A	141	962	1020	2.0-4.0	9.1	300	2.3	4.00	0.3
4B	141	965	1020	2.0-4.0	7.7	310	2.2	3.80	0.3
5A	140	970	1020	3.2-5.0	—	290	2.2	4.30	0.3
5B	140	960	1020	3.2-3.9	—	290	2.2	3.75	0.3

(b)

TABLE IV

SUMMARY OF TEST DATA FROM THE COTTRELL ENVIRONMENTAL SYSTEM'S FIRST TEST SERIES

(December, 1969)

Test No.	T-R Set B2 - Outlet Section					T-R Set A2 - Outlet Section				
	Spks/Min.	Volts AC	Amps AC	KVolts DC	Amps DC	Spks/Min.	Volts AC	Amps AC	KVolts DC	Amps DC
1A	—	—	—	—	—	0	305	70	34.4	0.30
1B	78	300	73	33.8	.26	—	—	—	—	—
2A	—	—	—	—	—	3	310	79	34.9	.32
3A	—	—	—	—	—	100	200	50	22.5	.26
3B	143	233	50	26.2	.14	—	—	—	—	—
4A	—	—	—	—	—	200	250	50	28.2	.24
4B	145	229	50	25.8	.13	—	—	—	—	—
5A	—	—	—	—	—	15	330	50	37.2	.24
5B	130	300	80	33.8	.32	—	—	—	—	—

(a)

Test No.	T-R Set B1 - Inlet Section					T-R Set A1 - Center Section				
	Spks/Min.	Volts AC	Amps AC	KVolts DC	Amps DC	Spks/Min.	Volts AC	Amps AC	KVolts DC	Amps DC
1A	150	330	60	37.2	.28	150	315	60	35.5	.33
1B	148	345	63	38.8	.30	145	330	73	37.2	.40
2A	85	355	75	40.0	.34	95	350	88	39.4	.50
3A	150	250	40	28.2	.12	150	278	50	31.2	.24
3B	160	233	35	26.2	.105	158	283	65	31.8	.35
4A	150	250	30	28.2	.12	150	265	50	29.8	.24
4B	160	228	34	25.6	.10	158	268	57	30.2	.28
5A	70	350	80	39.4	.40	118	330	90	37.2	.46
5B	85	305	73	34.4	.33	140	305	80	34.4	.44

(b)

TABLE V

SUMMARY OF TEST DATA FROM THE COTTRELL ENVIRONMENTAL SYSTEM'S FIRST TEST SERIES

(December, 1969)

Test No.	Power		Grain Loading @ 70°F & 30 "Hg-Gr/Ft^3			Removal Efficiency %			Migration Vel. W FPS/CMPS
	Watts / 1000 ACFM	Watts / 1000 Ft^2	MC Inlet	MC Outlet Pptr. Inlet	Pptr. Outlet	MC	ESP	Overall	
1	78	720	3.17	—	.036	—	—	98.7	—
1B	89	740	3.09	—	—	—	—	—	—
2A	102	940	—	—	—	—	—	—	—
3A	38	360	3.22	1.45	—	55.0	—	—	—
3B	40	360	3.14	1.37	0.227	56.4	83.5	92.6	.190/5.8
4A	42	410	2.73	1.19	—	56.5	—	—	—
4B	34	300	3.31	1.20	0.328	63.8	72.8	91.5	.18/5.5
5A	91	850	3.20	1.42	0.112	55.7	92.8	96.5	.41/12.5
5B	113	1000	2.95	1.26	0.045	57.3	96.4	98.3	.43/13.1

TABLE VI

SUMMARY OF TEST DATA FROM THE COTTRELL ENVIRONMENTAL SYSTEM'S SECOND TEST SERIES

(July, 1971)

Test No.	Unit Load MW	Steam M Lbs Per Hr.	Air M Lbs Per Hour	Flue Gas O_2 % by Vol.	Flue Gas H_2O % by Vol.	MC Inlet T. °F.	Δp "H_2O			Feed Rate Tons/Hr.		Bar. Press "Hg	Duct Press. ID Fan In. "H_2O	Elec. Precipitator		
							AH	MC	Pptr	Coal	Limestone			Inlet T. °F.	Gas Vol. M ACFM	Vel. FPS
1	139	975	1050	—	—	314	2.7	3.8	0.5	60.9	0	29.97	-13.5	293	299	6.7
2	136	890	1020	5.0	8.0	334	2.6	3.5	0.5	57.9	7.55	29.87	-13.2	314	292	6.6
3	137	920	980	4.4	5.8	270	2.2	2.8	0.3	55.5	8.50	29.79	-10.3	251	254	5.7
4	142	1050	1145	3.0	11.1	327	3.2	4.3	0.6	72.3	9.50	29.85	-14.8	305	357	[illegible]
5	140	1005	1095	—	6.2	265	2.4	3.2	0.4	64.6	4.75	29.83	-11.9	246	256	5.7
6	141	1000	1100	4.2	9.0	322	2.8	3.8	0.5	—	11.60	29.83	-13.5	301	302	6.9
8	142	1020	1100	3.2	7.0	276	2.6	3.5	0.5	62.9	11.15	29.76	-12.3	256	274	6.2
9	143	1010	1090	4.5	6.3	265	2.5	3.3	0.5	66.8	0	29.73	-11.5	246	264	5.9
10	143	1010	1100	3.1	8.0	270	2.5	3.3	0.5	67.5	16.75	29.69	-12.0	251	262	5.9
11	142	1010	1090	2.7	7.2	311	2.6	3.5	0.5	66.3	15.25	29.67	-12.5	220	234	5.4
14	138	980	1070	4.3	6.3	310	2.9	3.5	0.5	59.5	14.10	29.72	-12.6	289	285	6.4
15	141	1000	1070	4.4	7.3	263	2.5	3.2	0.4	62.6	14.45	29.71	-11.7	244	256	5.7
16	141	980	1040	4.2	5.8	260	2.5	3.3	0.5	58.5	0	29.89	-11.0	241	259	5.8
17	139	980	1035	5.3	5.6	262	2.4	3.2	0.4	57.2	9.70	29.90	-11.1	243	256	5.7
18	138	1000	1065	4.0	4.8	310	2.6	3.5	0.5	58.9	9.15	29.86	-12.0	289	282	6.3
19	137	980	1100	6.2	5.1	257	2.5	3.3	0.5	62.0	0	29.84	-12.0	238	259	5.8
20	140	998	1080	5.0	5.4	310	2.8	3.6	0.5	62.2	0	29.83	-12.8	289	288	6.5
21	140	980	1115	5.3	4.9	260	2.5	3.4	0.5	61.2	0	29.87	-12.0	241	264	5.9
22	139	980	1020	6.2	4.7	310	2.6	3.5	0.5	62.1	0	29.85	-12.1	289	282	6.3
23	139	980	1080	—	5.5	314	2.6	3.5	0.5	63.6	1.80	29.82	-12.2	292	284	6.4
24	140	980	1090	5.8	5.4	318	2.5	3.5	0.5	66.3	3.45	29.82	-12.1	296	284	6.4
25	136	960	1060	4.3	6.2	273	2.5	3.4	0.5	62.5	10.55	29.68	-11.8	253	268	6.0
26	141	993	1070	4.6	6.1	310	2.6	3.6	0.5	57.8	7.05	29.78	-12.1	289	286	6.4
27	139	980	1050	4.2	5.6	261	2.5	3.4	0.5	61.8	6.45	29.75	-11.7	242	265	6.0
28	138	1000	1065	5.2	4.7	311	2.7	3.7	0.5	61.2	11.15	29.90	-12.1	290	292	6.6
29	137	1000	1050	—	5.4	260	2.3	3.3	0.5	62.1	6.25	29.90	-11.1	241	259	5.8
30	139	1000	1064	4.8	6.1	309	2.7	3.7	0.5	62.6	3.30	29.89	-12.1	288	292	6.6
32	96	680	780	5.5	6.9	310	2.6	3.6	0.5	45.7	8.50	29.70	-10.0	289	288	6.5
33	136	980	1080	5.0	6.3	260	2.4	3.2	0.5	56.4	7.85	29.70	-11.2	241	259	5.8

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TABLE VII

SUMMARY OF TEST DATA FROM THE COTTRELL ENVIRONMENTAL SYSTEM'S SECOND TEST SERIES

(July, 1971)

Test No.	T-R Set B1--Inlet Section					T-R Set A1--Center Section					T-R Set B2--Outlet Section					Power		Grain Loading @ 70F & 30 "Hg-Gr/Ft.^{3}			Removal Efficiency, %			Migration Vel, W
	Spks/ Min.	Volts AC	Amps AC	K Volts DC	Amps DC	Spks/ Min.	Volts AC	Amps AC	K Volts DC	Amps DC	Spks/ Min.	Volts AC	Amps AC	K Volts DC	Amps DC	Watts/ 1000 ACFM	Watts/ 1000 Ft^2	MC Inlet	MC Outlet Pptr. Inlet	Pptr. Outlet	MC	ESP	Overall	FPS/cm PS
1	50	192	<10	22.9	.091	25	276	43	33.0	0.203	55	174	<10	20.8	.060	18.5	186	No Sample	Wet Sample	0.33	—	--	—	—
2	75	192	<20	23.8	.092	73	192	<10	21.75	0.083	100	187	<10	22.35	.040	9.5	93.3	5.46	1.95	0.44	64.3	77.4	91.9	0.24/7.3
3	112	159	<10	19.9	.061	70	172	<10	20.6	0.069	100	180	<5	21.5	.040	8.4	72.2	5.18	2.27	1.57	56.2	30.8	69.7	0.05/1.6
4	100	192	<10	22.9	.070	70	177	<5	21.2	0.060	105	154	<5	18.4	.014	4.7	57.1	3.23	2.21	1.63	31.6	26.2	49.6	0.06/1.8
5	100	169	<5	20.1	.070	70	188	<5	22.5	0.063	100	180	<5	21.5	.020	8.0	69.2	3.22	1.74	1.21	46.1	30.5	62.4	0.05/1.6
6	101	174	<5	21.2	.069	55	174	<5	20.8	0.060	110	167	<5	20.0	.011	9.5	96.2	6.37	2.36	1.95	62.8	17.4	69.3	0.03/1.0
8	57	240	33	31.1	.120	58	231	23	27.6	.114	100	242	50	28.9	.225	49.3	450	7.23	3.34	0.35	53.8	89.5	95.2	0.35/11.0
9	95	230	30	28.4	.120	73	221	17	26.4	.085	100	285	73	34.1	.330	64.0	569	—	1.22	0.12	—	90.2	—	0.34/10.4
10	95	244	27	29.2	.110	75	210	10	25.1	.080	100	263	45	31.4	186	42.2	372	—	2.18	0.12	—	94.5	—	0.43/13.1
11	100	191	17	21.1	.066	60	174	<5	20.8	.060	107	217	17	25.5	.081	17.1	164	—	3.78	0.75	—	80.2	—	0.26/7.9
14	102	191	<5	22.8	.061	70	174	<5	20.0	.060	29	203	<5	24.3	.061	14.5	139	8.15	3.93	0.93	51.8	76.3	88.6	0.33/10.1
15	59	232	13	28.4	.075	70	274	25	32.7	.098	0	237	25	28.3	.100	21.9	275	6.97	3.75	0.530	46.2	86.7	92.8	0.29/8.8
16	110	225	27	26.9	0.10	75	215	<5	25.8	.076	22	234	25	28.0	.103	25.2	254	—	1.43	0.390	—	72.65	—	0.19/5.7
17	100	220	25	26.3	0.08	75	203	<5	24.3	.060	20	235	24	28.1	.100	25.5	220	—	2.80	0.214	—	92.35	—	0.37/11.25
18	103	195	19	22.1	0.06	75	168	<5	21.1	.043	30	198	10	23.7	.048	11.8	112	—	2.395	0.847	—	64.9	—	0.165/5.0
19	99	316	71	37.9	0.44	53	270	58	32.3	0.327	0	266	84	31.0	.413	156.6	1366	—	3.10	0.19	—	93.9	—	0.41/12.5
20	95	265	58	31.7	0.27	55	271	55	32.4	0.281	0	264	77	31.5	.353	101.3	982	—	4.42	0.12	—	97.3	—	0.58/17.7
21	95	258	50	30.4	0.20	50	244	49	29.2	0.260	0	263	80	32.0	.389	99.8	867	—	2.48	0.13	—	94.8	—	0.44/13.4
22	93	214	43	25.5	0.17	67	211	14	25.2	0.11	27	239	65	28.6	0.30	55.1	524	—	2.81	0.29	—	89.7	—	0.36/11.0
23	99	189	57	22.5	0.24	68	171	<5	20.4	0.09	28	206	51	24.6	0.22	44.3	423	—	2.82	1.28	—	54.7	—	0.13/4.0
24	100	193	61	22.4	0.27	68	172	<5	20.6	0.09	30	195	43	23.5	0.15	42.0	402	—	2.92	1.17	—	60.0	—	0.15/4.4
25	95	237	54	29.3	0.25	58	220	37	26.3	0.15	0	245	66	29.3	0.30	74.7	674	—	3.59	0.13	—	96.4	—	0.50/15.3
26	101	194	13	23.2	0.07	75	173	<5	20.7	0.05	30	199	<5	23.3	0.05	13.4	179	—	2.20	0.74	—	66.2	—	0.17/5.3
27	99	247	22	29.5	0.11	69	245	10	29.3	0.09	21	236	15	28.2	0.10	33.2	295	—	2.44	0.42	—	82.8	—	0.26/8.0
28	100	215	25	25.7	0.10	64	190	12	22.7	0.11	24	215	43	25.7	0.12	33.9	334	—	3.27	0.56	—	82.9	—	0.29/8.8
29	100	211	25	25.2	0.09	75	201	<5	24.0	0.06	21	224	25	28.0	0.10	24.4	213	—	3.22	0.51	—	84.3	—	0.27/8.2
30	102	194	27	22.0	0.09	77	168	<5	20.1	0.05	30	193	29	23.7	0.11	20.3	199	—	3.49	1.15	—	67.0	—	0.18/5.5
32	99	222	27	25.5	0.11	69	214	10	25.5	0.10	8	253	51	30 2	0.21	40.9	396	9.23	4.61	0.24	50.1	94.8	97.4	0.48/14.5
33	75	275	45	32.3	0.19	60	253	55	30.2	0.17	<5	263	67	31.4	0.30	81.2	708	8.13	1.42	0.18	57.9	94.6	97.8	0.43/13.0

TABLE VIII

SUMMARY OF TEST DATA FROM TVA'S FIRST TEST SERIES

(July-August, 1969)

Test No.	Gas Flow M ACFM	Unit Load MW	Pptr. Eff. %	Pptr. Gas Temp. °F	Limestone Rate Tons/Hr	$\frac{\text{WATTS}}{10^3\ \text{ACFM}}$	$\frac{\text{WATTS}}{10^3\ \text{FT}^2}$	MIGRATION VELOCITY W FT/SEC.	MIGRATION VELOCITY W CM/SEC.	GRAIN LOADING @32°F-29.92"Hg OUTLET grs./ft^3
4	258	140	95.8	303	0	94.3	818	0.46	13.9	0.0712
5	252	142	95.6	303	0	98.9	839	0.44	13.4	0.0697
7	200	134	97.2	308	0	132.2	890	0.40	12.2	0.0491
16	227	130	98.0	312	0	108.8	831	0.50	15.2	0.0309
24	282	144	94.9	304	0	101.4	963	0.47	14.3	0.0952
25	302	143	94.4	304	0	92.9	945	0.49	14.9	0.1284
27	250	125	96.7	271	0.	102.0	858	0.48	14.6	0.0496
28	241	124	97.6	271	0	130.1	1056	0.50	15.4	0.0398
30	216	139	97.8	268	0	210.9	1534	0.46	14.1	0.0266
31	221	141	98.4	268	0	202.4	1506	0.51	15.6	0.0215
33	235	137	96.6	272	0	108.3	930	0.48	14.7	0.0455
34	237	137	95.7	272	0	100.1	866	0.45	13.8	0.0559
36	295	138	93.7	323	0	87.9	873	0.46	13.9	0.0792
38	327	137	95.8	317	0	136.0	1498	0.58	17.7	0.0596
39	324	136	94.0	317	0	104.4	1139	0.51	15.6	0.0839
41	340	137	94.9	308	0	108.9	1247	0.57	17.3	0.0837
42	373	136	95.0	308	0	88.2	1108	0.63	19.1	0.076

TABLE IX

SUMMARY OF TEST DATA FROM TVA'S FIRST TEST SERIES

(July-August, 1969)

Test No.	T-R SET 1A (FULL WAVE)					T-R SET 1A (FULL WAVE)					T-R SET 3A (FULL WAVE				
	Spks/Min	PRI Volts AC	PRI Amps AC	SEC. Amps DC	KV Avg.	Spks/Min	PRI Volts AC	PRI Amps AC	SEC. Amps DC	KV Avg.	Spks/Min	PRI Volts AC	PRI. Amps AC	SEC. Amps DC	KV Avg.
4	154	335	84	0.22	40.	129	341	86	0.215	40.8	148	269	51	0.21	32.1
5	195	342	86	0.22	40.8	150	360	83	0.215	43.0	145	267	46	0.21	31.9
7	214	335	97	0.25	40.0	193	327	92	0.22	39.1	141	285	50	0.23	34.0
16	329	345	90	0.22	41.2	105	358	85	0.21	42.8	148	278	50	0.20	33.2
24	27	360	89	0.245	43.0	12	372	83	0.205	44.5	143	268	59	0.28	32.0
25	40	363	93	0.26	43.4	14	377	86	0.22	45.1	145	262	50	0.22	31.3
27	140	329	90	0.235	39.3	121	348	78	0.20	41.6	143	266	48	0.25	31.8
28	291	284	87	0.22	33.9	139	317	72	0.195	37.9	167	337	78	0.41	40.3
30	78	342	102	0.29	40.9	63	358	94	0.255	42.8	1	318	105	0.60	38.0
31	132	320	98	0.29	38.2	100	326	94	0.24	38.9	2	323	106	0.62	39.2
33	167	324	89	0.24	38.7	130	344	80	0.21	41.1	140	280	62	0.29	33.5
34	177	348	88	0.235	41.6	132	332	75	0.195	39.7	142	265	48	0.26	31.7
36	69	333	93	0.255	39.8	47	372	81	0.20	44.5	143	275	47	0.21	32.9
38	15	350	111	0.325	41.8	15	350	111	0.325	41.8	123	315	84	0.46	37.6
39	16	351	112	0.33	41.9	16	351	112	0.33	41.9	145	245	48	0.21	29.3
41	28	336	112	0.325	40.2	28	336	112	0.325	40.7	135	286	64	0.32	34.7
42	92	322	106	0.29	38.5	92	322	106	0.29	38.5	138	296	65	0.30	35.4

TABLE X

SUMMARY OF TEST DATA FROM TVA'A SECOND TEST SERIES

(June-July, 1970)

Test No.	Gas Flow- M ACFM	Unit Load- MW	Pptr. Eff. %	Pptr. Gas Temp-°F	Ultimate Coal Analysis (Dry) Ash %	Sulphur %	Ash Sulphur Ratio	Lime-stone Rate Tons/Hr.	Coal Rate Tons/Hr.
4	286	140	89.4	309	14.4	2.0	7.2	0	62.5
5	255	140	73.4	309	15.0	1.4	10.7	11.0	62.5
9	247	142	83.3	303	14.2	2.2	6.5	9.5	64
10	234	127	86.8	315	13.3	2.9	4.6	0	56.5
11	239	130	70.3	315	13.9	4.1	3.4	9.0	58
13	271	140	84.3	315	14.3	2.9	4.9	0	62.5
14	266	141	70.9	315	19.9	2.4	8.3	5.0	63
15	269	144	70.9	315	23.8	2.5	9.5	9.5	68
17	277	140	81.4	317	16.7	2.7	6.2	0	62.5
18	278	143	61.2	317	23.7	2.6	9.1	5.0	66.5
19	250	145	47.0	317	28.6	2.4	11.9	10.0	69
21	283	141	73.3	320	14.5	2.1	6.9	0	63
23	301	143	85.7	311	19.2	2.4	8.0	0	66.5
24	295	141	68.7	311	16.6	3.4	4.9	10	63
26	296	141	92.3	311	16.7	3.1	5.4	0	63
27	300	142	68.8	311	16.3	2.6	6.3	5.5	64
28	302	142	67.9	311	15.1	2.4	6.3	9.5	64
30	279	134	94.7	313	18.9	3.3	5.7	0	59.5
31	277	134	78.8	313	17.3	2.9	6.0	5.15	59.5
32	279	134	81.8	313	18.5	3.0	6.2	10.0	59.5
34	298	140	83.8	316	21.8	2.5	8.7	5.0	62.5
35	289	141	76.3	316	15.3	3.0	5.1	10.0	63
36	289	140	86.3	316	15.7	2.9	5.4	0	62.5
38	314	143	85.8	314	18.3	2.7	6.8	5.5	66.5
39	311	144	78.2	314	15.4	3.0	5.1	10.0	68
40	311	144	79.8	314	15.3	2.8	5.5	0	68
42	306	142	91.3	316	17.7	3.4	5.2	0	64
43	306	143	82.7	316	16.1	3.0	5.4	4.5	66.5

TABLE XI

SUMMARY OF TEST DATA FROM TVA'S SECOND TEST SERIES

(June-July, 1970)

Test No.	WATTS / 10^3 ACFM	WATTS / 10^3 FT^2	MIGRATION VELOCITY W, ft/sec	MIGRATION VELOCITY W, cm/sec	GRAIN LOADING @ 32°F and 29.92"Hg OUTLET grs/ft^3
4	35.9	346	0.36	10.9	0.153
5	27.3	262	0.21	6.4	0.448
8	44.1	367	0.24	7.5	0.294
10	35.7	281	0.26	8.1	0.195
11	10.10	81	0.16	4.9	0.652
13	27.4	250	0.28	8.5	0.167
14	10.7	96	0.18	5.6	0.522
15	8.3	75	0.18	5.6	0.648
17	15.6	146	0.26	7.9	0.364
18	9.7	91	0.14	4.5	0.675
19	7.0	66	0.10	3.0	1.139
21	14.7	140	0.21	6.3	0.362
23	48.8	494	0.32	10.0	0.211
24	32.2	324	0.19	5.9	0.474
26	88.6	883	0.42	12.9	0.145
27	23.1	234	0.19	5.9	0.431
28	23.3	237	0.19	5.8	0.536
30	149.8	1407	0.46	14.0	0.1728
31	34.4	321	0.24	7.3	0.395
32	20.6	193	0.26	8.1	0.377
34	69.8	700	0.30	9.2	0.299
35	41.10	399	0.23	7.1	0.477
36	50.5	491	0.32	9.8	0.237
38	53.2	563	0.34	10.4	0.270
39	47.8	500	0.26	8.1	0.416
40	53.9	564	0.27	8.5	0.158
42	67.3	693	0.41	12.7	0.126
43	40.7	420	0.30	9.1	0.264

TABLE XII

SUMMARY OF TEST DATA FROM TVA'S SECOND TEST SERIES

(June-July, 1970)

Test No.	T-R SET 1A (FULL WAVE)					T-R SET 2A (FULL WAVE)					T-R SET 3A (FULL WAVE)				
	SPKS/Min.	PRI Volts AC	PRI Amps AC	Sec. Amps DC	KV Avg.	SPKS/Min.	PRI Volts AC	PRI Amps AC	SEC. Amps DC	KV Avg.	SPKS/Min.	PRI Volts AC	PRI Amps AC	SEC. Amps DC	KV Avg.
4	0	285	65	0.15	34.0	120	250	30	0.08	29.8	155	233	50	0.10	27.8
5	0	275	70	0.155	32.8	125	225	22	0.05	26.8	160	190	125	0.06	22.7
8	0	250	38	0.06	29.8	[illegible]	250	43	0.105	29.8	500	250	40	0.20	29.8
10	185	250	35	0.06	29.8	160	255	45	0.09	30.4	180	200	15	0.16	23.9
11	210	200	0	0.03	23.9	170	220	20	0.05	26.2	190	160	0	0.02	19.1
13	180	260	30	0.065	31.0	145	255	55	0.135	34.0	185	170	16	0.04	20.5
14	195	190	10	0.03	32.7	[illegible]	220	27	0.05	26.2	195	180	12	0.04	21.5
15	180	162	0	0.015	19.3	[illegible]	250	42	0.02	23.9	215	205	25	0.06	24.4
17	215	230	15	0.06	27.4	[illegible]	245	70	0.08	28.6	190	165	0	0.02	19.7
18	215	205	10	0.03	24.4	[illegible]	220	10	0.06	26.2	185	165	0	0.02	19.7
19	215	200	10	0.03	23.9	[illegible]	210	10	0.05	25.0	190	135	0	0	16.1
21	205	220	20	0.035	26.2	[illegible]	260	35	0.085	31.0	185	170	15	0.03	20.3
23	140	255	40	0.035	30.4	[illegible]	250	34	0.075	29.8	150	330	50	0.25	39.4
24	145	225	35	0.06	26.8	[illegible]	220	25	0.06	26.2	155	225	45	0.24	[illegible]
26	150	330	75	0.18	39.4	[illegible]	300	63	0.155	35.8	150	325	60	0.35	38.8
27	165	225	23	0.06	26.9	[illegible]	220	20	0.06	26.2	155	210	22	0.15	25.0
28	165	220	20	0.05	26.2	[illegible]	220	20	0.06	26.2	160	205	20	0.17	24.4
30	30	385	115	0.3	46.0	[illegible]	295	74	0.23	35.2	142	370	55	0.45	44.2
31	165	235	38	0.085	38.0	[illegible]	250	42	0.105	29.8	155	240	32	0.14	28.6
32	165	230	33	0.073	27.4	[illegible]	230	25	0.075	27.4	155	195	17	0.07	23.8
34	590	270	65	0.16	32.2	[illegible]	250	70	0.20	33.4	500	250	45	0.30	29.8
[illegible]	490	250	60	0.12	[illegible]	[illegible]	250	55	0.14	31.0	500	220	40	0.15	26.2
36	485	280	60	0.14	33.4	[illegible]	275	52	0.145	32.8	500	240	40	0.18	28.8
39	490	270	58	0.135	[illegible]	[illegible]	235	69	0.20	34.0	500	245	40	0.19	29.2
[illegible]	495	265	53	0.125	31.5	[illegible]	270	67	0.205	32.2	500	225	32	0.16	[illegible]
40	480	290	60	0.145	34.6	[illegible]	295	67	0.195	35.2	500	240	37	0.17	28.8
42	150	310	80	0.145	37.0	[illegible]	300	65	0.185	35.8	155	320	60	0.24	[illegible]
43	160	270	60	0.11	32.2	[illegible]	265	45	0.125	31.6	210	260	40	0.16	31.0

TABLE XIII

SUMMARY OF TEST DATA FROM TVA'S SECOND TEST SERIES

(June-July, 1970)

Test No.#	Gas Flow M ACFM	Unit Load MW	Pptr. Eff. %	Pptr. Gas Temp. °F	Ultimate Coal Analysis (Dry) Ash %	Ultimate Coal Analysis (Dry) Sulphur %	Ash / Sulphur Ratio	Lime-stone Rate Tons/Hr.	Coal Rate Tons/Hr.
44	299	144	85.3	316	15.9	2.7	5.9	9.5	68
46	295	142	92.6	306	17.1	2.7	6.3	0	64
47	283	139	77.3	306	15.8	2.7	5.9	5.0	62
48	280	140	83.4	306	15.7	3.0	5.2	10.0	62.5
50	239	142	93.7	307	14.0	2.7	5.2	0	64
51	237	142	91.1	313	14.0	2.8	5.0	5.0	64
52	239	143	89.6	320	14.3	3.0	4.8	10.0	66.5
54	285	140	89.8	310	13.7	2.7	5.1	0	62.5
55	285	141	71.3	310	13.6	2.8	4.9	3.3	63
56	280	141	79.3	310	13.7	2.8	4.9	2.25	63
58	279	142	94.9	304	14.0	2.8	5.0	0	64
59	279	142	88.3	304	13.2	2.7	4.9	2.3	64
60	283	144	82.0	304	12.9	2.5	5.2	1.25	68
61	302	141	91.6	304	13.8	2.6	5.3	0	63
62	296	143	81.3	304	14.0	2.6	5.4	1.2	66.5
64	294	142	93.4	310	14.2	3.1	4.6	0	64
65	293	142	82.6	310	13.6	2.8	4.9	5.0	64
66	290	142	74.0	310	13.6	2.6	5.2	10.5	64
68	287	140	85.6	309	14.8	2.5	5.9	0	62.5
69	275	140	78.6	309	16.3	2.4	6.8	1.4	62.5
70	273	142	78.8	309	15.8	2.4	6.6	5.5	64
72	227	139	88.5	311	20.2	2.5	8.1	0	62
73	222	140	88.0	311	14.0	2.4	5.8	1.3	62.5
74	223	143	87.2	311	16.2	2.4	6.8	5.5	66.5

TABLE XIV

SUMMARY OF TEST DATA FROM TVA'S SECOND TEST SERIES

(June-July, 1970)

Test No.#	WATTS / 10^3 ACFM	WATTS / 10^3 FT^2	MIGRATION VELOCITY W ft/sec	MIGRATION VELOCITY W cm/sec	GRAIN LOADING @ 32°F and 29.92"Hg OUTLET grs/ft^3
44	21.7	219	0.32	9.8	0.319
46	62.7	623	0.43	13.1	0.1022
47	19.7	187	0.23	7.2	0.311
48	18.1	171	0.28	8.6	0.329
50	72.3	582	0.37	11.3	0.0990
51	33.8	269	0.32	9.8	0.145
52	29.5	237	0.30	9.2	0.228
54	57.1	548	0.36	11.1	0.149
55	21.6	207	0.20	6.1	0.362
56	20.5	193	0.24	7.5	0.334
58	63.2	593	0.46	14.2	0.0870
59	27.1	255	0.33	10.2	0.246
60	22.1	211	0.27	8.3	0.279
61	59.6	606	0.42	12.8	0.0965
62	34.6	345	0.27	8.5	0.243
64	94.1	931	0.44	13.6	0.0941
65	30.7	302	0.28	8.8	0.362
66	22.1	216	0.21	6.6	0.418
68	41.4	400	0.31	9.5	0.214
69	24.3	225	0.23	7.2	0.319
70	21.7	199	0.23	7.2	0.352
72	61.5	470	0.27	8.4	0.129
73	34.4	257	0.26	8.0	0.162
74	32.4	243	0.25	7.8	0.214

TABLE XV

SUMMARY OF TEST DATA FROM TVA'S SECOND TEST SERIES

(June-July, 1970)

Test No. #	T-R SET 1A (FULL WAVE)					T-R SET 2A (FULL WAVE)					T-R SET 3A (FULL WAVE)				
	SPKS/Min	PRI Volts AC	PRI Amps AC	SEC Amps DC	KV Avg.	SPKS/Min.	PRI Volts AC	PRI Amps AC	SEC. Amps DC	KV Avg.	SPKS/Min	PRI Volts AC	PRI Amps AC	SEC. Amps DC	KV Avg.
44	170	235	35	0.07	28.083	170	240	30	0.06	28.680	270	215	25	0.110	25.6
46	155	295	55	0.145	35.253	160	290	57	0.155	34.655	160	280	45	0.24	33.4
47	165	230	30	0.065	27.485	180	230	30	0.07	27.485	170	195	25	0.08	23.3
48	170	225	30	0.065	26.888	185	225	27	0.065	26.888	170	190	25	0.07	22.7
50	160	320	60	0.14	38.240	165	230	56	0.135	33.460	160	270	50	0.23	32.2
51	165	240	35	0.08	28.680	180	245	33	0.085	29.278	165	225	29	0.12	26.8
52	165	230	31	0.07	27.485	180	235	30	0.08	28.083	165	220	24	0.11	26.2
54	160	255	40	0.085	30.473	165	290	60	0.14	34.655	160	285	45	0.26	34.0
55	165	240	30	0.07	28.680	180	230	30	0.08	27.485	165	205	20	0.08	24.4
56	165	235	30	0.065	28.083	180	230	30	0.08	27.485	168	205	20	0.07	24.4
58	160	290	47	0.105	34.655	170	260	47	0.11	31.070	155	295	60	0.30	35.2
59	165	260	30	0.075	31.070	180	240	28	0.08	28.680	163	225	20	0.11	26.8
60	165	235	30	0.07	28.083	180	235	30	0.075	28.083	165	205	20	0.09	24.4
61	155	310	70	0.15	37.045	140	300	60	0.17	35.850	160	280	40	0.19	33.4
62	160	290	50	0.10	34.655	165	255	45	0.115	31.668	165	220	27	0.12	26.2
64	150	315	70	0.175	37.643	145	300	61	0.175	35.850	120	335	67	0.37	40.0
65	165	240	37	0.08	28.680	170	240	35	0.085	28.680	180	210	23	0.17	25.0
66	158	230	30	0.07	27.485	170	235	31	0.08	28.083	182	210	19	0.09	25.0
68	160	285	50	0.105	34.058	160	275	50	0.13	32.863	175	260	29	0.13	30.0
69	165	250	37	0.08	29.875	170	240	32	0.09	28.680	180	205	20	0.07	24.4
70	165	250	35	0.07	29.875	170	240	30	0.085	28.680	180	195	20	0.06	23.3
72	160	310	60	0.13	37.045	155	270	50	0.13	32.265	175	260	37	0.16	32.0
73	162	255	35	0.075	30.473	175	245	32	0.08	29.278	180	230	25	0.11	27.4
74	165	240	37	0.065	28.680	175	245	32	0.08	29.278	180	230	27	0.11	27.4

TABLE XVI

COAL ANALYSES FOR BOTH COTTRELL ENVIRONMENTAL SYSTEM'S TEST SERIES

(December, 1969 & July, 1971)

Run(1) No.	Moisture	Vol. Comb. Matter	Fixed Carbon	Ash	Sulfur				Ash / Sulfur
					Pyritic	Organic	Sulfate	Total	
1A&1B	10.10	33.93	44.52	11.45	1.44	1.32	0.04	2.80	4.2
2A	5.90	36.10	45.89	12.11	2.24	1.44	0.04	3.72	3.3
3A	9.90	35.66	45.89	10.78	1.25	0.88	0.02	2.15	5.0
3B	10.40	34.59	43.86	11.15	0.82	1.06	0.02	1.90	5.9
4A	9.40	35.53	45.90	9.17	1.16	1.52	0.03	2.71	3.4
4B	8.80	34.93	43.83	12.44	0.94	0.92	0.03	1.89	6.6
5A&5B	8.00	36.43	45.79	9.78	1.67	1.52	0.03	3.22	3.0
1	10.30	30.69	45.62	13.39	1.39	0.88	0.10	2.37	5.6
2	11.00	31.92	43.06	14.02	1.41	1.01	0.13	2.55	5.5
3	9.30	32.93	44.35	13.42	1.47	0.96	0.12	2.55	5.3
4	10.90	29.40	41.28	18.42	0.66	0.67	0.04	1.37	13.5
5	10.80	31.96	42.64	14.60	1.59	0.96	0.14	2.69	5.4
6	8.70	31.74	41.55	18.01	1.64	0.91	0.08	2.63	6.9
8	10.90	32.39	42.60	14.11	1.48	1.00	0.11	2.59	5.4
9	10.50	32.39	41.06	16.05	0.78	0.77	0.07	1.62	9.9
10	10.80	32.61	40.20	16.39	0.77	0.79	0.04	1.60	10.2
11	11.10	30.92	41.57	16.41	0.82	0.80	0.06	1.68	9.8
14	9.20	35.06	41.73	14.01	1.55	1.08	0.06	2.69	5.2
15	10.10	32.59	44.16	13.15	1.27	0.89	0.06	2.22	5.9
16	8.30	32.87	45.34	13.49	0.72	0.70	0.03	1.45	9.3
17	8.40	31.99	45.48	14.13	0.92	0.67	0.03	1.62	8.7
18	8.60	30.81	46.80	13.79	1.24	0.84	0.05	2.13	6.5
19	7.90	29.13	43.08	19.89	0.22	0.59	0.03	0.84	23.7
20	8.20	29.22	42.71	19.87	0.24	0.57	0.04	0.85	23.4
21	7.20	30.32	43.89	18.59	0.25	0.58	0.03	0.86	21.6
22	6.90	30.28	43.63	19.19	0.30	0.63	0.02	0.95	20.2
23	8.90	28.82	41.13	21.15	0.35	0.68	0.04	1.07	19.8
24	8.90	28.86	40.09	22.15	0.36	0.80	0.06	1.22	18.1
25	7.40	32.92	41.18	18.50	1.07	0.87	0.06	2.00	9.3
26	8.70	31.92	46.08	13.30	1.28	0.94	0.05	2.27	5.9
27	8.20	36.36	42.59	12.85	1.04	0.65	0.04	1.73	7.4
28	7.20	34.81	39.76	18.23	1.74	1.46	0.14	3.34	5.5
29	10.20	33.00	41.70	15.10	1.18	1.02	0.10	2.30	6.6
30	8.50	33.26	42.45	15.79	1.36	1.22	0.08	2.66	5.9
32.	10.90	34.69	37.44	16.97	2.70	1.26	0.10	4.06	4.2
33	5.60	36.47	37.99	19.94	2.25	1.57	0.22	4.04	4.9

TABLE XVII

COAL ANALYSES FOR TVA'S FIRST TEST SERIES

(July-August, 1969)

TVA TEST NO.	MOISTURE	VOL. COMB. MATTER	FIXED CARBON	ASH	TOTAL SULFUR	HEATING VALUE BTU/LB.	$\frac{\text{ASH}}{\text{SULFUR}}$
4	11.9	34.62	42.99	10.48	2.73	11,189	3.8
5	12.2	33.80	42.85	11.15	3.16	10,993	3.5
7	13.0	32.80	42.72	11.48	3.39	10,823	3.4
16	9.2	35.05	42.77	12.98	2.63	11,168	4.9
24	9.4	34.34	43.94	12.32	3.08	11,298	4.0
25	9.6	33.99	44.93	11.48	2.44	11,327	4.7
27	11.4	31.36	43.50	13.73	2.04	10,738	6.7
28	10.9	32.34	43.93	12.83	2.41	10,968	5.3
30	9.9	35.50	44.42	10.18	2.70	11,533	3.8
31	10.3	34.44	44.67	10.58	2.69	11,401	3.9
33	10.7	32.24	45.63	11.43	2.14	11,171	5.3
34	10.9	31.90	45.98	11.26	1.69	11,191	6.7
36	8.8	34.11	44.41	12.68	3.01	11,300	4.2
38	8.3	34.39	45.57	11.74	3.39	11,545	3.5
39	8.3	34.85	44.75	12.10	3.76	11,527	3.2
41	7.9	33.89	45.04	13.17	3.59	11,448	3.7
42	8.3	34.00	46.07	11.33	3.02	11,580	3.8

TABLE XVIII

COAL ANALYSES FOR BABCOCK AND WILCOX PILOT TEST PROGRAM

(1967-1969)

	STANDARD TEST COALS COLBERT STEAM PLANT			TVA TEST COALS				LIGNITE COAL	HIGH SULFUR COAL
	B-22791 1st Shipment	C-13167 2nd Shipment 1st Box	C-13331 2nd Shipment 2nd Box	C-13273 Orient #3 Mine	C-13274 Atkinson Mine	C-13279 Old Ben #24 Mine	C-13319 Little Joe Mine	C-13376 North Dakota Lignite	C-13378 Peabody Coal Company
Proximate Analysis % Dry									
Volatile Matter	37.4	38.8	37.6	35.5	34.4	38.8	37.0	43.3	32.4
Fixed Carbon	47.4	48.2	47.9	49.8	46.7	50.2	46.9	48.0	35.0
Ash	15.2	13.0	14.5	14.7	18.9	11.0	16.1	8.7	32.6
BTU/lb Dry	12,150	12,560†	--	12,150	11,360	12,760	11,980	11,020	9.330
Ultimate Analysis % Dry									
Carbon	67.5	68.7	--	--	--	--	--	65.6	49.0
Hydrogen	4.6	4.9	--	--	--	--	--	4.5	3.7
Nitrogen (Calculated)	1.3	1.4	--	--	--	--	--	1.4	1.0
Sulfur	4.3	4.2	--	--	--	--	--	0.7	13.2
Ash	15.2	12.8	--	--	--	--	--	8.7	32.6
Oxygen (Difference)	7.1	8.0	--	--	--	--	--	19.1	0.5
Sulfur Forms % Dry gas Sulfur									
Pyritic	2.7	1.4	--	0.8	2.6	1.3	1.9	0.1	10.9
Sulfate	0.1	0.9	--	<0.1	0.2	<0.1	0.1	<0.1	0.3
Organic (Difference)	1.5	1.9	--	0.6	1.2	1.3	1.6	0.6	2.0
Total	4.3	4.2	4.2	1.4	4.0	2.6	3.6	0.7	13.2
Chlorine % Dry	0.02	0.07	--	--	--	--	0.03	--	--
Ash Composition %									
SiO_2	39.	36.	--	52.	42.	45.	51.	25.	30.
Al_2O_3	16.	13.	--	24.	17.	22.	24.	8.	18.
Fe_2O_3	27.	28.	--	9.0	18.	17.	18.	11.	45.
TiO_2	0.5	0.4	--	0.6	0.4	0.5	0.5	0.4	0.4
CaO	9.0	9.0	--	6.0	13.	6.0	1.0	24.	1.0
MgO	0.3	0.5	--	2.0	0.9	1.0	1.0	9.0	0.4
Na_2O	0.6	0.6	--	1.4	0.6	1.3	0.5	3.0	0.3
K_2O	2.2	2.3	--	1.9	1.6	1.7	2.4	0.4	1.3
SO_3 (Gravimetric)	3.4	12.9	--	--	--	--	--	--	--
Ash Fusion Temperature °F* Atmosphere	Red. Oxid.	Red. Oxid.	Red. Oxid.	Red. Oxid.	Red. Oxid.	Red. Oxid.	Red. Oxid.	Red. Oxid.	Red. Oxid.
IT	1940 2240	1950 2250	-- --	2070 2200	1950 2160	2070 2270	1990 2440	2270 2280	1990 2370
SS	1990 2300	2000 2340	-- --	2270 2410	1990 2220	2140 2360	2170 2480	2350 2320	2070 2510
SH	2060 2340	2040 2380	-- --	2330 2460	2020 2250	2180 2410	2240 2500	2380 2340	2110 2550
FT 1/16	2340 2460	2310 2500	-- --	2740 2670	2270 2440	2650 2670	2680 2710	2450 2370	2480 2570
FT (flat)	2370 2510	2390 2540	-- --	2880 2860	2480 2540	2780 2750	2710 2800	2550 2430	2510 2580

†Calc. Btu (DuLong)
*ASTM Designations

TABLE XIX

PARTICLE SIZE ANALYSES FOR COTTRELL ENVIRONMENTAL SYSTEM'S FIRST TEST SERIES

(December, 1969)

Run No.	Cumulative Per Cent By Weight Less Than Indicated Particle Diameter									SP.GR. gm/cc	Sample Source
	Bahco					Sieve					
	2μ	5μ	10μ	20μ	30μ	44μ	74μ	149μ	297μ		
1A	5.8	18.0	30.0	41.0	48.0	66.2	74.0	95.2	98.6	2.17	Mech. Inlet
1B	10.2	23.0	42.2	62.0	71.8	69.0	97.0	97.9	99.8	2.65	Mech. Inlet
3A	6.4	17.0	28.6	43.0	53.0	74.0	84.0	95.0	99.4	2.16	Mech. Inlet
4A	2.8	12.2	26.0	44.4	46.0	87.0	92.8	98.0	99.7	2.31	Mech. Inlet
4B	4.8	13.0	28.0	49.2	62.4	86.2	87.2	95.4	99.7	2.58	Mech. Inlet
5A	3.0	13.8	26.2	42.0	51.0	77.8	84.8	92.2	95.6	2.41	Mech. Inlet
5B	4.2	16.8	30.2	35.6	54.0	84.0	85.0	92.4	96.0	2.26	Mech. Inlet
2A	6.9	37.0	68.8	89.6	95.5	86.2	90.4	95.0	97.8	2.40	Pptr. Inlet
3A	11.9	48.0	74.2	90.4	95.0	89.0	92.4	95.8	98.0	2.16	Pptr. Inlet
3B	10.6	46.6	76.6	93.2	97.2	91.2	94.2	97.0	98.3	2.24	Pptr. Inlet
4A	12.5	49.4	78.	93.6	97.4	92.0	96.8	98.6	99.1	2.40	Pptr. Inlet
4B	12.0	49.2	78.0	93.6	97.4	90.0	95.2	97.9	99.0	2.41	Pptr. Inlet
5A	9.2	43.6	75.6	94.2	98.2	89.4	93.6	97.0	98.8	2.34	Pptr. Inlet
5B	11.5	46.0	76.2	94.0	98.0	92.4	95.2	97.8	99.1	2.53	Pptr. Inlet
2A	13.8	50.0	73.8	89.2	94.2	86.0	88.0	93.5	97.8	1.97	Pptr. Outlet
3A	25.4	48.4	76.0	93.8	96.8	82.0	88.8	95.8	98.0	1.71	Pptr. Outlet
3B	9.0	40.6	81.8	92.5	94.8	73.4	83.8	91.5	95.6	2.05	Pptr. Outlet
4B	13.6	52.6	79.0	92.0	95.0	86.5	89.8	94.0	97.0	2.20	Pptr. Outlet
1A&1B	2.2	8.2	20.8	40.6	50.4	86.2	89.6	98.9	99.7	1.64	Mech. Coll. Hopper & Catch
2A	3.8	10.8	24.0	45.4	59.8	78.0	94.2	97.8	99.4	—	Mech. Pptr.
3B&4B	2.2	7.4	17.0	34.0	47.4	82.5	87.2	98.0	99.6	2.38	Mech. Coll. Hopper & Catch
3A&4A	3.4	10.8	24.2	41.0	48.2	86.0	89.0	98.7	99.78	2.38	Mech. Coll. Hopper & Catch
5A&5B	3.4	9.8	20.2	37.8	50.0	86.5	89.8	97.8	99.72	2.37	Mech. Pptr. Hopper
1A&1B	17.5	58.0	81.5	93.2	96.8	38.0	91.5	98.6	99.6	2.15	Electrostatic Collector
2A	13.0	49.6	78.0	94.0	97.8	89.0	94.5	99.0	99.6	2.26	Elect. Pptr. Hopper
3A&4A	13.0	48.0	86.0	93.0	97.2	68.0	96.8	99.5	99.9	1.64	Elect. Pptr. Hopper & Catch
5A&5B	14.8	51.0	79.8	95.0	98.2	63.0	93.0	98.2	99.5	2.21	Elect. Pptr. Hopper & Catch

TABLE XX

PARTICLE SIZE ANALYSES FOR COTTRELL ENVIRONMENTAL SYSTEM'S SECOND TEST SERIES

(July, 1971)

Run No.	Cumulative Per Cent By Weight Less Than Indicated Particle Diameter									SP.GR. gm/cc	Sample Source
	Bahco					Sieve					
	2μ	5μ	10μ	20μ	30μ	44μ	74μ	149μ	297μ		
6	16.5	42.0	61.5	75.0	79.5	92.8	97.5	100.0	100.0	2.68	Limestone Feed Tank
8	19.2	47.5	67.5	79.0	82.0	94.3	99.1	100.0	100.0	2.61	Limestone Feed Tank
14	10.8	28.0	42.0	49.0	52.0	62.5	64.4	79.2	94.0	2.60	Limestone Feed Tank
23	15.5	44.0	65.0	77.0	81.5	97.1	99.2	99.9	100.0	2.51	Limestone Feed Tank
24	15.0	43.0	65.0	76.0	80.0	96.0	97.9	99.9	100.0	2.34	Limestone Feed Tank
32	10.0	28.0	43.5	52.0	55.0	64.5	82.2	85.6	96.0	2.54	Limestone Feed Tank
33	9.7	27.5	42.5	51.0	54.5	62.4	78.5	82.4	95.5	2.50	Limestone Feed Tank
2	8.2	33.5	55.8	76.0	84.8	92.9	97.1	99.41	99.78	2.85	Mech. Inlet
2	9.0	36.0	83.0	95.5	96.9	93.6	94.6	95.8	97.6	2.80	Pptr. Inlet
2	10.8	50.0	82.5	93.6	94.9	90.6	91.6	93.2	96.9	2.75	Pptr. Outlet
3	7.0	32.4	54.0	74.0	83.0	90.4	96.2	99.3	99.7	2.49	Mech. Inlet
3	6.4	38.4	71.0	92.8	97.4	99.25	99.5	99.8	99.9	2.48	Pptr. Inlet
3	3.6	18.1	41.0	67.0	80.0	90.0	94.6	99.15	99.76	2.36	Pptr. Outlet
4	7.8	46.0	81.2	95.5	97.4	98.3	98.6	99.04	99.1	3.07	Pptr. Inlet
4	9.0	40.8	72.4	92.4	97.2	93.5	94.3	95.4	97.9	2.56	Pptr. Outlet
5	4.4	20.2	44.0	70.0	82.0	88.9	92.1	95.5	98.3	1.89	Mech. Inlet
5	7.0	39.8	74.0	94.0	98.2	95.4	95.8	97.2	98.9	3.11	Pptr. Inlet
5	7.0	38.0	72.0	90.0	94.2	39.1	59.1	76.2	87.0	2.86	Pptr. Outlet
6	5.2	22.4	46.0	71.0	83.8	92.1	94.4	98.9	99.6	2.70	Mech. Inlet
6	6.8	40.0	75.8	95.0	98.6	97.3	98.3	98.8	99.2	2.30	Pptr. Inlet
6	4.0	34.4	68.4	88.2	93.0	99.4	99.7	99.9	99.96	1.38	Pptr. Outlet
8	5.2	21.6	44.0	68.4	80.5	89.0	95.6	98.1	98.8	2.39	Mech. Inlet
8	8.2	47.0	79.6	95.0	98.0	99.3	99.5	99.87	99.92	2.66	Pptr. Inlet
8	—	—	—	—	—	65.7	89.3	97.8	99.1	—	Pptr. Outlet
9	—	—	—	—	—	66.5	94.1	96.2	99.4	2.31	Pptr. Inlet
10	5.0	31.0	65.8	88.8	95.0	96.4	97.2	97.5	97.8	2.63	Pptr. Inlet
11	6.0	38.8	75.0	4.8	97.5	98.3	99.2	99.8	99.9	2.50	Pptr. Inlet
11	5.8	31.2	71.8	91.5	96.6	96.6	97.6	99.9	99.99	3.19	Pptr. Outlet
14	4.8	20.0	41.0	65.2	77.6	86.2	92.9	95.5	98.6	2.53	Mech. Inlet
14	9.2	46.0	79.8	96.0	98.9	99.5	99.5	99.7	99.7	2.91	Pptr. Inlet
14	3.5	29.6	60.0	85.5	93.[illegible]	99.5	99.5	99.5	99.94	2.91	Pptr. Outlet
15	7.4	25.0	46.4	69.6	80.5	91.6	95.1	98.9	99.4	2.48	Mech. Inlet
15	3.8	32.0	70.0	93.5	98.2	98.7	98.9	99.0	99.2	2.55	Pptr. Inlet
16	3.5	28.6	65.0	91.0	97.0	98.3	98.8	99.5	99.5	2.50	Pptr. Inlet

TABLE XXI

PARTICLE SIZE ANALYSES FOR COTTRELL ENVIRONMENTAL SYSTEM'S SECOND TEST SERIES

(July, 1971)

Run No.	C lative Per Cent By Weight Less Than Indicated Particle Diameter										
	Bahco					Sieve				SP.GR. gm/cc	Sample Source
	2µ	5µ	10µ	20µ	30µ	44µ	74µ	149µ	297µ		
17	5.0	29.8	62.0	87.8	95.0	98.0	98.5	99.4	99.8	2.47	Pptr. Inlet
18	6.5	38.0	73.0	93.6	98.0	97.9	98.3	99.3	99.6	2.09	Pptr. Inlet
18	—	—	—	—	—	95.9	96.6	98.6	99.6	—	Pptr. Outlet
19	11.0	42.0	63.8	81.0	88.0	92.2	97.9	99.1	99.77	2.37	Pptr. Inlet
20	6.5	30.0	52.0	73.6	91.0	65.9	93.0	99.0	99.77	2.51	Pptr. Inlet
21	13.6	52.0	82.0	96.2	98.8	98.6	99.0	99.45	99.64	2.62	Pptr. Inlet
22	13.0	51.8	82.0	96.4	99.0	98.2	98.9	99.4	99.7	2.63	Pptr. Inlet
23	16.0	56.0	85.0	97.2	99.4	98.3	98.8	99.2	99.4	2.67	Pptr. Inlet
23	15.0	55.6	84.0	94.2	96.2	98.3	98.9	99.5	99.9	2.21	Pptr. Outlet
24	14.0	57.2	84.5	96.0	98.3	97.6	97.9	98.6	98.8	2.75	Pptr. Inlet
24	13.2	52.2	79.8	93.0	96.0	98.2	98.8	99.4	99.8	2.76	Pptr. Outlet
25	8.8	44.6	77.0	93.2	96.5	98.8	99.1	99.5	99.7	2.71	Pptr. Inlet
26	11.2	51.8	83.0	96.0	98.4	98.1	98.6	99.0	99.4	4.33	Pptr. Inlet
26	7.8	38.0	69.6	89.8	94.2	93.2	96.6	97.6	98.8	2.63	Pptr. Outlet
27	4.4	25.6	61.0	88.2	95.8	98.6	99.1	99.5	99.8		Pptr. Inlet
27	—	—	—	—	—	—	—	—	—	—	Pptr. Outlet
28	13.2	59.6	85.6	96.2	98.2	98.0	98.4	98.9	99.2	2.89	Pptr. Inlet
28	—	—	—	—	—	90.6	97.1	99.1	99.6	2.83	Pptr. Outlet
29	5.0	37.8	78.4	94.5	97.4	97.9	98.1	98.7	99.1	2.37	Pptr. Inlet
30	—	—	—	—	—	90.9	98.3	99.1	99.5	2.66	Pptr. Outlet
30	10.6	50.4	79.6	93.8	98.0	98.6	99.0	99.3	99.6	3.02	Pptr. Inlet
30	22.2	70.0	90.2	96.5	97.8	98.4	98.9	99.5	99.7	3.93	Pptr. Outlet
32	9.6	31.6	42.0	71.4	79.6	93.3	94.8	98.2	99.8	2.62	Mech. Inlet
32	9.8	48.0	80.4	95.4	98.2	99.4	99.7	99.8	99.9	2.69	Pptr. Inlet
33	18.2	44.0	64.0	78.2	84.0	95.6	97.5	99.3	99.7	3.11	Mech. Inlet
33	10.0	48.4	80.8	95.8	98.6	98.8	99.2	99.6	99.9		Pptr. Inlet
2	4.8	14.6	28.2	48.0	60.2	88.3	94.7	99.7	99.99	2.85	Mechanical Hoppers "B" Side 1, 2, 5, 6
3	4.4	14.2	27.6	45.0	56.0	84.1	95.7	99.9	100.00	2.98	
5	3.5	12.5	26.0	44.0	56.0	88.1	91.1	99.4	99.99	2.52	
6	2.8	10.2	22.2	39.6	51.0	79.7	87.8	99.2	99.93	2.49	
8	3.6	13.0	27.0	46.0	58.0	90.5	93.5	99.5	99.92	2.71	
14	2.8	11.8	22.4	36.8	46.0	64.9	87.0	96.1	99.5	2.83	
15	2.2	11.6	23.0	38.0	48.0	64.7	87.6	94.0	99.6	3.04	
32	2.8	12.6	24.2	40.2	50.2	83.2	82.2	96.3	99.7	2.74	
33	3.0	10.8	23.0	40.0	51.8	79.5	87.0	97.3	99.7	2.80	

TABLE XXII

PARTICLE SIZE ANALYSES FOR COTTRELL ENVIRONMENTAL SYSTEM'S SECOND TEST SERIES

(July, 1971)

Run No.	Cumulative Per Cent By Weight Less Than Indicated Particle Diameter										
	Bahco					Sieve				SP.GR. gm/cc	Sample Source
	2µ	5µ	10µ	20µ	30µ	44µ	74µ	149µ	297µ		
15	17.8	60.4	88.2	98.2	99.58	99.9	99.9	100.00	100.00	2.63	Electrical Pptr. ← Hoppers "B" → Side 1, 2, 5, 6
16	16.8	58.0	86.0	97.4	99.3	99.8	99.94	99.96	100.00	2.29	
14	15.8	59.6	87.0	97.2	99.1	99.8	99.8	99.95	99.95	2.43	
17	16.2	61.6	88.0	97.8	99.2	99.5	99.6	99.7	100.00	2.65	
18	17.2	62.0	88.2	98.1	99.5	99.9	99.99	100.00	100.00	2.75	
21	14.0	54.0	89.0	92.6	94.5	96.9	97.6	99.6	99.95	2.16	
22	17.5	61.8	86.0	96.2	98.4	98.3	98.7	99.5	99.8	2.46	
23	17.5	57.8	82.8	95.0	97.9	98.1	98.8	99.8	99.91	2.55	
24	18.0	58.0	82.8	94.2	96.9	97.3	99.2	99.7	100.00	2.56	

TABLE XXIII

LABORATORY AND IN-SITU RESISTIVITY MEASUREMENTS FOR COTTRELL ENVIRONMENTAL SYSTEM'S FIRST TEST SERIES

(December, 1969)

Run No.	Sample Source	Lab Resistivity - OHM CM (6% Moisture in Gas)					Temp °F	In-Situ Resistivity
		250°F.	350°F.	430°F.	550°F	650°F.		
1A	AH Inlet						509	1.4×10^{10}
1B	AH Inlet						510	4.3×10^{10}
3A	AH Inlet						520	1.3×10^{10}
4A	AH Inlet						520	1.2×10^{10}
5A	AH Inlet						634	3.7×10^{9}
5B	AH Inlet						638	1.1×10^{10}
1A	MC	1.1×10^{13}	1.4×10^{12}	1.6×10^{11}	1.1×10^{10}	1.1×10^{9}		
1B	MC	1.4×10^{14}	1.5×10^{13}	1.6×10^{12}	1.8×10^{11}	1.2×10^{10}		
3A	MC	1.4×10^{13}	2.5×10^{12}	2.3×10^{11}	1.2×10^{10}	9.0×10^{8}		
4A	MC	2.1×10^{12}	9.0×10^{11}	6.8×10^{10}	9.0×10^{9}	9.0×10^{8}		
4B	MC	9.0×10^{12}	1.4×10^{13}	1.1×10^{12}	1.2×10^{11}	1.8×10^{10}		
5A	MC	1.9×10^{12}	1.7×10^{11}	4.5×10^{10}	6.8×10^{9}	1.2×10^{9}		
5B	MC	5.4×10^{12}	1.3×10^{12}	1.1×10^{12}	3.4×10^{11}	6.8×10^{10}		
2A	Pptr. Inlet	1.2×10^{12}	9.0×10^{11}	5.4×10^{11}	4.5×10^{10}	6.8×10^{9}	293	4.8×10^{9}
3A	Pptr. Inlet	1.4×10^{12}	5.4×10^{11}	5.4×10^{10}	6.8×10^{9}	9.0×10^{8}	318	2.1×10^{10}
3B	Pptr. Inlet	1.6×10^{12}	9.0×10^{11}	1.1×10^{11}	9.0×10^{10}	5.4×10^{8}	293	2.6×10^{11}
4A	Pptr. Inlet	1.6×10^{12}	6.8×10^{11}	9.0×10^{10}	6.8×10^{9}	9.0×10^{8}	312	4.7×10^{10}
4B	Pptr. Inlet	2.5×10^{12}	1.8×10^{12}	2.7×10^{11}	1.8×10^{10}	1.5×10^{9}	302	3.0×10^{11}
5A	Pptr. Inlet	9.0×10^{12}	1.6×10^{12}	1.7×10^{11}	9.0×10^{9}	1.1×10^{9}		
5B	Pptr. Inlet	5.4×10^{12}	1.5×10^{12}	1.6×10^{11}	9.0×10^{9}	1.4×10^{9}		
2A	Pptr. Outlet	6.8×10^{12}	1.4×10^{12}	1.7×10^{11}	1.1×10^{10}	1.1×10^{9}		
3A	Pptr. Outlet	1.2×10^{12}	3.9×10^{11}	1.5×10^{11}	1.4×10^{10}	1.3×10^{9}		
3B	Pptr. Outlet	1.0×10^{12}	5.4×10^{11}	1.4×10^{11}	1.5×10^{10}	1.2×10^{9}		
4B	Pptr. Outlet	1.4×10^{11}	2.7×10^{11}	6.8×10^{10}	6.8×10^{9}	6.8×10^{8}		
5B	Pptr. Outlet	1.1×10^{12}	4.5×10^{11}	1.6×10^{10}	3.9×10^{9}	6.8×10^{8}		

TABLE XXIV

LABORATORY AND IN-SITU RESISTIVITY MEASUREMENTS FOR COTTRELL ENVIRONMENTAL SYSTEM'S SECOND TEST SERIES

(July, 1971)

Run No.	Source Sample	Lab Resistivity - OHM-CM (6% Moisture in Gas)							Temp. °F	In-Situ Resistivity
		200°F.	250°F.	300°F.	350°F.	400°F.	500°F.	600°F.		
19	Pptr. Inlet	3.4×10^{13}	5.4×10^{13}	4.5×10^{13}	3.9×10^{13}	5.4×10^{12}	3.4×10^{11}	1.9×10^{10}	260	2.8×10^{10}
20	Pptr. Inlet	4.5×10^{10}	2.1×10^{13}	2.7×10^{13}	2.3×10^{13}	9.0×10^{12}	5.4×10^{11}	5.4×10^{10}	330	1.8×10^{11}
21	Pptr. Inlet	9.0×10^{12}	1.4×10^{14}	2.3×10^{13}	1.4×10^{13}	4.5×10^{12}	2.1×10^{11}	1.3×10^{10}	260	1.4×10^{11}
22	Pptr. Inlet	1.6×10^{13}	5.4×10^{13}	2.7×10^{13}	2.7×10^{13}	9.0×10^{12}	1.4×10^{12}	1.1×10^{11}	322	1.8×10^{11}
23	Pptr. Inlet	6.8×10^{12}	6.8×10^{13}	4.5×10^{13}	3.9×10^{13}	2.7×10^{13}	2.7×10^{12}	9.0×10^{11}	323	3.7×10^{12}
24	Pptr. Inlet	9.0×10^{12}	2.7×10^{14}	1.4×10^{14}	9.0×10^{13}	6.8×10^{13}	9.0×10^{13}	1.4×10^{13}	328	2.9×10^{12}
26	Pptr. Inlet	3.0×10^{12}	--	9.0×10^{13}	--	1.4×10^{14}	3.4×10^{13}	1.4×10^{13}	320	5.9×10^{12}
32	Pptr. Inlet	3.0×10^{11}	--	6.8×10^{13}	--	1.4×10^{14}	1.4×10^{14}	6.8×10^{13}	325	8.3×10^{11}
33	Pptr. Inlet	2.7×10^{12}	--	3.9×10^{13}	--	5.4×10^{13}	3.9×10^{13}	6.8×10^{12}	260	9.1×10^{11}
1	Pptr. Inlet								315	1.1×10^{11}
2	Pptr. Inlet								312	1.2×10^{12}
3	Pptr. Inlet								250	5.7×10^{10}
4	Pptr. Inlet								325	1.6×10^{11}
5	Pptr. Inlet								268	2.1×10^{11}
6	Pptr. Inlet								323	5.6×10^{11}
8	Pptr. Inlet								285	1.6×10^{11}
9	Pptr. Inlet								280	3.8×10^{11}
10	Pptr. Inlet								260	6.7×10^{11}
11	Pptr. Inlet								320	6.5×10^{11}
14	Pptr. Inlet								320	8.9×10^{11}
15	Pptr. Inlet								262	1.4×10^{11}
16	Pptr. Inlet								270	2.9×10^{12}
17	Pptr. Inlet								262	2.3×10^{11}
18	Pptr. Inlet								310	5.6×10^{11}
[illegible]	Pptr. Inlet								270	1.4×10^{12}
25	Pptr. Inlet								326	2.4×10^{11}
27	Pptr. Inlet								272	1.5×10^{11}
[illegible]	Pptr. Inlet								265	4.3×10^{11}
30	Pptr. Inlet								320	9.0×10^{12}

TABLE XXV

LABORATORY AND IN-SITU RESISTIVITY MEASUREMENTS FOR COTTRELL ENVIRONMENTAL SYSTEM'S SECOND TEST SERIES

(July, 1971)

Run No.	Source Sample	Lab Resistivity - OHM-CM (6% Moisture in Gas)						Temp. °F.	In-Situ Resistivity
		200°F	300°F	400°F	500°F	600°F	650°F		
4	Pptr. Inlet	2.7×10^{9}	6.8×10^{11}	2.5×10^{12}	1.6×10^{12}	2.7×10^{11}	1.4×10^{11}	325	1.6×10^{11}
9	Pptr. Inlet	4.5×10^{6}	2.7×10^{9}	9.0×10^{10}	1.3×10^{10}	3.0×10^{9}	1.8×10^{9}	280	3.8×10^{11}
10	Pptr. Inlet	3.3×10^{10}	9.0×10^{11}	1.3×10^{13}	3.4×10^{12}	2.5×10^{11}	9.0×10^{10}	260	6.7×10^{11}
25	Pptr. Inlet	4.5×10^{12}	3.9×10^{13}	9.0×10^{13}	2.7×10^{13}	5.4×10^{12}	3.9×10^{12}	270	1.4×10^{12}
30	Pptr. Inlet	3.9×10^{12}	3.4×10^{13}	4.5×10^{13}	1.8×10^{13}	3.0×10^{12}	1.8×10^{12}	320	9.0×10^{12}

TABLE XXVI

LABORATORY AND IN-SITU RESISTIVITY MEASUREMENTS FOR BABCOCK AND WILCOX PILOT TEST PROGRAM

(1967-1969)

Legend	Test No.	Coal No.	Laboratory Resistivity, ohm-cm			In Situ Resistivity, ohm-cm	
			300 F	600 F	At In Situ Temp	Temp, F	Resistivity
●	67-[illegible]-1	B-22791	3.2×10^{12}	6.7×10^{10}	-	-	-
	68-4-1		4.0×10^{12}	2.0×10^{10}	9.0×10^{10}	505	1.0×10^{10}
	68-7-10		1.8×10^{13}	3.9×10^{11}	1.8×10^{13}	299	2.7×10^{10}
	68-4-11		-	-	-	460	1.6×10^{10}
	68-5-2		-	-	-	425	4.3×10^{9}
	69-2-11		-	-	-	300	1.9×10^{11}
○	69-4-2	C-13167	2.5×10^{12}	8.4×10^{9}	1.0×10^{12}	270	1.7×10^{11}
	69-4-4		3.4×10^{12}	6.8×10^{9}	2.5×10^{12}	310	1.6×10^{11}
	69-4-5		2.7×10^{13}	6.8×10^{11}	2.7×10^{13}	300	2.6×10^{10}
	69-4-6		2.7×10^{12}	3.9×10^{10}	2.5×10^{12}	305	2.6×10^{10}
	69-[illegible]-8		-	-	-	300	1.3×10^{11}
▲	69-4-13	C-13273	1.2×10^{12}	6.8×10^{9}	1.0×10^{12}	310	1.1×10^{11}
	69-4-15		-	-	-	310	1.8×10^{11}
△	69-4-19	C-13274	2.1×10^{12}	4.5×10^{9}	2.1×10^{12}	300	3.4×10^{11}
	69-4-21		-	-	-	320	4.4×10^{10}
⬢	69-4-25	C-13279	4.5×10^{11}	6.8×10^{9}	4.0×10^{11}	310	4.6×10^{11}
	69-5-1		-	-	-	305	3.1×10^{11}
	69-5-5		-	-	-	355	7.2×10^{10}
⬡	69-7-7	C-13319	4.5×10^{12}	6.8×10^{9}	4.0×10^{12}	313	5.7×10^{10}
■	69-11-11	C-13376	1.5×10^{11}	1.4×10^{9}	1.3×10^{11}	400	3.2×10^{10}
	69-11-13		-	-	-	365	6.2×10^{9}
□	69-[illegible]2-5	C-13378	8.4×10^{12}	5.4×10^{9}	8.0×10^{12}	295	1.4×10^{12}

TABLE XXVII

SUMMARY OF CHEMICAL ANALYSES PERFORMED ON SAMPLES TAKEN DURING THE FIRST CES TEST SERIES

Test Date	Sample Identification	CES Test No.	TVA Lab No.	% SiO_2	% Al_2O_3	% Fe_2O_3	% CaO	% MgO	% TiO_2	% Na_2O	% K_2O	% $SO_4^=$	% Loss on Ignition
12-11-69	MC Inlet	1A	C-34	46.8	20.9	16.7	7.0	1.0	0.7	0.8	2.2	1.3	2.2
12-11	MC Hopper	—	C-48	46.3	20.2	16.9	7.1	1.0	0.9	0.6	1.7	1.6	2.6
12-11	ESP Hopper	—	C-53	49.9	23.2	10.6	4.7	1.2	1.1	0.8	2.0	2.8	2.7
12-11	MC Inlet	1B	C-35	46.8	20.1	16.3	6.4	1.1	0.9	0.7	2.2	1.8	3.9
12-12	MC Outlet	2A	C-41	48.0	20.7	14.2	5.4	1.0	1.0	0.6	2.3	2.5	2.8
12-12	MC Hopper	—	C-49	45.6	20.0	18.2	6.7	1.1	0.9	0.5	1.7	1.5	2.3
12-12	ESP Hopper	—	C-54	47.4	21.4	13.6	5.3	1.2	1.1	0.6	1.9	2.5	2.8
12-13	MC Outlet	3B	C-43	49.8	24.1	9.7	4.5	1.3	1.0	1.0	2.3	1.2	3.1
12-13	MC Inlet	4B	C-38	46.5	20.9	13.6	6.7	1.0	0.7	0.9	2.0	1.0	4.6
12-13	MC Outlet	4B	C-45	50.1	23.7	10.1	4.5	1.4	0.9	1.0	2.1	1.2	2.7
12-13	MC Hopper	—	C-51	46.0	20.6	14.6	7.7	1.1	1.0	0.6	1.7	1.1	3.1
12-14	MC Inlet	3A	C-36	47.6	21.9	16.4	6.6	1.0	0.7	0.7	2.0	0.9	2.2
12-14	MC Outlet	3A	C-42	50.1	24.5	10.1	4.0	1.5	1.0	0.9	2.3	1.6	2.3
12-14	MC Inlet	4A	C-37	47.3	21.1	16.0	6.3	0.9	0.7	0.8	2.0	1.1	2.4
12-14	MC Outlet	4A	C-44	50.6	24.0	10.2	4.1	1.2	1.0	1.0	2.2	1.5	2.1
12-14	MC Hopper	—	C-50	45.6	19.9	17.9	6.9	1.0	0.8	0.5	1.4	0.8	4.0
12-14	ESP Hopper	—	C-55	50.3	24.0	10.1	4.2	1.3	1.1	0.8	1.9	1.7	2.8
12-15	MC Inlet	5A	C-39	43.4	19.8	25.1	3.5	1.0	0.8	0.4	1.8	0.9	3.2
12-15	MC Outlet	5A	C-46	50.1	23.4	14.1	2.4	1.2	1.0	0.5	2.0	1.6	2.6
12-15	MC Inlet	5B	C-40	42.6	19.3	22.0	3.8	0.9	0.9	0.4	1.8	0.7	5.0
12-15	MC Outlet	5B	C-47	49.6	23.0	14.1	2.9	1.3	1.0	0.5	1.9	1.3	3.0
12-15	MC Hopper	—	C-52	43.6	18.5	24.0	4.6	1.0	0.9	0.3	1.4	0.8	3.1
12-15	ESP Hopper	—	C-56	49.8	22.9	12.6	3.1	1.4	1.1	0.6	1.9	1.6	2.5
-	AH Inlet	—	C-57	47.4	21.0	13.5	5.9	1.2	1.1	0.7	1.7	2.2	3.2

TABLE XXVIII

SUMMARY OF CHEMICAL ANALYSES PERFORMED ON SAMPLES TAKEN DURING THE SECOND CES TEST SERIES

Test Date	Sample Identification	CES Test No.	TVA Lab No.	% $S^=$	% $SO_4^=$	% $SO_3^=$	Total %S	% CaO
7-10-71	MC Inlet	2	C-883	<0.1	6.4	6.7	4.8	30.8
"	MC Outlet	2	C-881		7.8	10.8	6.9	28.6
"	ESP Outlet	2	C-882		6.3	2.0	2.9	19.9
"	MC Hopper	2	C-774		4.9	0.1	1.7	32.5
"	ESP Hopper	2	C-773		6.7	0.1	2.3	24.2
7-13-71	MC Inlet	6	C-895		4.8	7.8	4.7	33.0
"	MC Outlet	6	C-893		5.6	10.5	6.1	30.0
"	ESP Outlet	6	C-894		4.0	3.0	2.5	30.2
"	MC Hopper	6	C-790		2.6	0.3	1.0	22.0
"	ESP Hopper	6	C-789		4.6	1.1	2.0	32.5
7-14-71	MC Inlet	8	C-898		5.3	9.6	5.6	33.3
"	MC Outlet	8	C-896		6.6	12.3	7.1	31.4
"	ESP Outlet	8	C-897		5.0	8.5	5.1	22.1
"	MC Hopper	8	C-794		4.4	0.2	1.6	37.5
"	ESP Hopper	8	C-793		4.7	0.5	1.7	24.1
7-15-71	MC Outlet	9	C-899		4.4	<0.1	1.5	4.5
"	MC Outlet	10	C-901		4.5	11.7	6.2	23.5
"	MC Outlet	11	C-903		5.2	7.9	4.9	31.6
7-24-71	MC Inlet	14	C-907		5.4	8.2	5.1	35.6
"	MC Outlet	14	C-905		7.3	7.9	5.6	33.9

TABLE XXVIII (continued)

SUMMARY OF CHEMICAL ANALYSES PERFORMED ON SAMPLES TAKEN DURING THE SECOND CES TEST SERIES

Test Date	Sample Identification	CES Test No.	TVA Lab No.	% $S^=$	% $SO_4^=$	% $SO_3^=$	Total %S	% CaO
7-24-71	ESP Outlet	14	C-906	<0.1	5.6	5.0	3.9	28.0
"	MC Hopper	14	C-814		4.5	0.5	1.7	46.5
"	ESP Hopper	14	C-813		5.2	0.9	2.1	24.6
7-24-71	MC Inlet	15	C-910		5.6	7.7	5.0	36.7
"	MC Outlet	15	C-908		6.9	10.8	6.6	34.7
"	ESP Outlet	15	C-909		5.5	5.5	4.0	26.6
"	MC Hopper	15	C-817		4.3	0.6	1.7	49.3
"	ESP Hopper	15	C-816		6.0	1.1	2.4	31.4
7-22-71	--	17	C-912		4.4	6.5	4.0	26.9
7-22-71	MC Outlet	18	C-915		5.5	7.5	4.8	33.6
7-20-71	MC Outlet	19	C-917		0.8	0.3	0.4	1.4
"	ESP Outlet	19	C-918		4.4	3.7	2.9	9.8
"	ESP Hopper	19	C-830		0.6	0.1	0.3	1.7
"	MC Outlet	20	C-919		0.8	0.9	0.6	2.2
"	ESP Outlet	20	C-920		7.2	4.4	4.2	13.4
"	ESP Hopper	20	C-832		0.8	<0.0	0.3	2.2
7-20-71	MC Outlet	21	C-921		0.8	0.2	0.4	1.1
"	ESP Outlet	21	C-922		5.3	3.0	2.9	11.8
"	ESP Hopper	21	C-835	↓	0.8	<0.1	0.3	1.4
"	MC Outlet	22	C-923		1.6	0.6	0.8	5.6

TABLE XXVIII (continued)

SUMMARY OF CHEMICAL ANALYSES PERFORMED ON SAMPLES TAKEN DURING THE SECOND CES TEST SERIES

Test Date	Sample Identification	CES Test No.	TVA Lab No.	% $S^=$	% $SO_4^=$	% $SO_3^=$	Total %S	% CaO
"	ESP Outlet	22	C-924	<0.1	3.7	1.1	1.7	6.2
"	ESP Hopper	22	C-838	↓	0.7	<0.1	0.3	2.8
"	MC Outlet	23	C-925	↓	1.9	1.1	1.1	5.9
"	ESP Outlet	23	C-926	↓	2.5	1.4	1.4	16.2
"	ESP Hopper	23	C-842	↓	1.6	<0.1	0.6	9.8
"	MC Outlet	24	C-927	↓	4.0	1.9	2.1	18.8
"	ESP Outlet	24	C-928	↓	3.7	1.4	1.8	17.6
"	ESP Hopper	24	C-846	↓	3.0	<0.1	1.0	15.1
7-19-71	MC Outlet	25	C-929	↓	5.9	8.6	5.4	26.0
7-23-71	MC Outlet	26	C-931	↓	6.0	7.6	5.0	30.8
"	MC Outlet	27	C-934	↓	5.3	8.5	5.2	28.8
7-21-71	MC Outlet	28	C-936	↓	8.4	2.8	3.9	38.6
"	MC Outlet	29	C-938	↓	6.9	4.1	3.9	28.8
"	MC Outlet	30	C-940	↓	6.7	5.0	4.2	27.2
7-26-71	MC Inlet	32	C-944	↓	6.5	4.5	4.0	27.7
"	MC Outlet	32	C-942	↓	8.7	9.7	6.8	27.7
"	ESP Outlet	32	C-943	↓	7.2	10.6	6.6	23.5
"	MC Hopper	32	C-873	↓	4.5	0.4	1.7	29.7
"	ESP Hopper	32	C-872	↓	7.1	0.3	2.5	24.9

TABLE XXVIII (continued)

SUMMARY OF CHEMICAL ANALYSES PERFORMED ON SAMPLES TAKEN DURING THE SECOND CES TEST SERIES

Test Date	Sample Identification	CES Test No.	TVA Lab No.	% $S^=$	% $SO_4^=$	% $SO_3^=$	Total %S	% CaO
7-26-71	MC Inlet	33	C-947	<0.1	6.0	6.7	4.7	25.5
"	MC Outlet	33	C-945	↓	8.3	7.9	5.9	26.3
"	ESP Outlet	33	C-946	↓	6.4	10.8	6.4	21.0
"	MC Hopper	33	C-877	↓	4.6	0.3	1.6	31.6
"	ESP Hopper	33	C-876	↓	8.8	0.2	3.0	26.6

TABLE XXIX

CHEMICAL ANALYSES OF LIMESTONE USED DURING SECOND CES TEST SERIES

Test Date	Sample Identification	CES Test No.	TVA Lab No.	% H_2O (105°C)	% CaO	% MgO	% $CO_3^=$
7-10-71	Limestone 98% Gyroclass (Fine)	2	C-772	0.1	54.9	0.2	55.6
7-24-71	Limestone 20% Gyroclass (Coarse)	14	C-812	<0.1	54.9	0.2	55.7
7-26-71	Limestone 20% Gyroclass (Coarse)	32	C-871	<0.1	55.0	0.2	55.0

VI. ANALYSIS AND DISCUSSION OF TEST RESULTS

The main sources of data used in the analysis and correlation of the test results are two CES test programs at Shawnee (December 1969 and July 1971), two TVA test programs (July-August 1969 and June-July 1970) SRI test program at Shawnee during July 1971, Research-Cottrell, Inc., tests at a midwest power station during limestone injection tests (February 1967) and Babcock and Wilcox pilot plant study (1967-1970).

1. Electrostatic Precipitator Performance

The precipitator is a Research-Cottrell, Inc., design installed on the unit 10 steam generator at TVA Shawnee Station, Paducah, Kentucky. The boiler is a B&W pulverized coal, front-fired unit rated at 175 megawatts designed to produce one million pounds of steam per hour at 1800 psig and 1000/1000° F. The dust collecting equipment is a Buell mechanical cyclone designed for 65% efficiency followed by the Research-Cottrell, Inc., precipitator designed for 95% efficiency. (Overall design efficiency is 98%.)

The boiler is fired with about 60 tons per hour of coal containing an average of 10% ash and 2.7% sulfur. Combustion of this fuel produces about 585,000 cfm of flue gas at 300° F containing 2200 ppm by volume SO_2 and about 3 grains of fly ash per standard cubic foot.

The precipitator shown in Figure 15 consists of two units ("A" and "B") each including three sections as follows:

Inlet Section of 33 opzel plate ducts each 9" x 30" high x 4.5' long.
Center Section of 33 opzel plate ducts each 9" x 30' high x 4.5' long.
Outlet Section of 33 opzel plate ducts each 9" x 30' high x 6.0' long.

There are 20 magnetic impulse-gravity impact rappers per precipitator and 4 electrical sets with automatic control rated at 70 KV_{peak} 750 ma each.

The total collecting area of the precipitator is 59,400 ft^2. The cross-sectional area is 1,485 ft^2. The secondary electrical readings, i.e. those at the precipitator can be estimated from the following expression using the transformer primary readings:

$$\text{Sec. } KV_{avg.} = (0.1195)\ (\text{primary voltage}_{\text{AC Volts}}) \qquad (12)$$

$$\text{Sec. } I_{ma} = \left[(5.96)\ (\text{primary current}_{\text{AC amps}}) - 77.2\right] \qquad (13)$$

The first basis for analysis of precipitator performance was a function of corona power input. A brief look at theoretical considerations of this approach follows.

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A. Theoretical Considerations of Electrostatic Precipitator Performance As A Function of Corona Power

$$1\text{-}E = Q = \frac{-A}{W} W \tag{14}$$

$$W = \frac{d_p \; E_o \; E_p}{4 \; \pi \; \eta} \tag{15}$$

where,

E = Fractional efficiency of precipitator
Q = Fractional loss from precipitator
A = Collecting electrode area of precipitator
V = Gas flow rate through precipitator
W = Precipitation rate parameter
d_p = Particle diameter
E_o = Charging field in precipitator
E_p = Precipitating field in precipitator
η = Gas viscosity

Combining equations (14) and (15) gives:

$$\ln Q = \left(-\frac{A}{V}\right)\left(\frac{d_p \; E_o \; E_p}{4 \; \pi \; \eta}\right) \tag{16}$$

Both theoretical and experimental considerations have shown that:

$$P_c = \propto A \, E_o \, E_p \tag{17}$$

where

P_c = Precipitator corona power input
$\propto$ = Precipitation parameter dependent upon gas and particle characteristics, and precipitator electrode geometry to a minor extent.

Equation (16) can be rewritten as:

$$\ln Q = - \frac{d_p}{4 \pi \eta \propto} \; \frac{P_c}{V} \tag{18}$$

Thus, for similar particle size, and gas and particle characteristics, Equation (18) shows that:

$$\ln Q = -k \frac{P_c}{V} = -\frac{A}{V} W \tag{19}$$

From which is obtained the relationship that:

$$\frac{P_c}{A} = \frac{W}{k}, \text{ or} \tag{20}$$

W is directly proportional to precipitator corona power/ft^2 of collecting electrode, which means that by doubling the corona power to a precipitator designed for 90% efficiency, one can theoretically increase the efficiency to about 99%. However, for practical considerations, the attainment of the corona power in a precipitator necessary to obtain the design efficiency requires the examination of factors which determine and affect corona power.

(a) Particle Characteristics

(1) Particle Size - This can reduce corona power by suppressing corona current at a given voltage through space charge phenomena. However, sub-micron particles of fairly high loadings are necessary in order to produce a significant affect.

(2) Electrical Resistivity - When the ash resistivity exceeds about 10^{10} to 10^{11} ohm-cm, the effective corona power is reduced. Generally, the first effect is increased sparking requiring a voltage reduction in order to hold a preselected sparkrate. Lower corona current and power input results causing a decrease in collection efficiency. In order to compensate for the lower power, it becomes necessary to enlarge the precipitator until the total power requirements for the desired efficiency are met. Note that the corona power per unit area of precipitator is lower, but increased area, increases the total corona power to the desired level.

With very high dust resistivity, a condition known as "back corona" sets in, characterized by very high currents, low voltages and no sparking. Precipitation practically stops and can only be restored by lowering the dust resistivity.

On the other hand, extremely conductive particles of less than about 10^4 ohm-cm may be reentrained and escape collection.

(b) Gas Characteristics

(1) Temperature - Increase in gas temperature, normally reduces the voltage at which a precipitator will spark, but the corona current at any given voltage increases. Further, the corona current at which a precipitator sparks is not significantly changed by temperature, but the voltage is reduced, resulting in a net decrease in corona power as temperature increases and vice versa.

(2) Pressure - Small increases in gas pressure raise the precipitator sparking voltage proportionately while the corona current decreases at a fixed voltage. Again, the corona current at sparking is not significantly changed, so that the net effect is to increase corona power as gas pressure increases and vice versa.

(3) Composition - Determines the kind of gas ions formed in corona. Electronegative and high molecular weight gases tend to form low mobility ions, reducing corona current and raising sparking voltage.

Gases such as sulfur trioxide and water vapor condition the ash by affecting its electrical resistivity. Sulfur trioxide is a critical factor which depends mainly on the amount of sulfur in the coal. However, excess air, residence time of sulfur dioxide in an optimum temperature zone, catalytic materials in the ash such as iron oxide, etc., can also influence the amount of sulfur trioxide present. Generally, mositure is not effective as a conditioning agent until low gas temperatures are reached, e.g. 200-225° F, and even then large amounts (percents) are required, while concentrations on the order of parts per million by volume of sulfur trioxide can radically change precipitator performance.

B. Correlation Of Precipitator Performance With Corona Power Input

The data used for this analysis are taken from Tables III through XV. In order to establish a baseline operating condition of corona power input and precipitator performance, only tests without limestone injection have been used for the first correlation. In Figure 19, the precipitation rate parameter W in ft/sec is plotted as a function of corona power input expressed as a density parameter, i.e. kilowatts/1000 ft^2 of precipitator collecting surface. From equation 20, expectations are that the correlation will be a linear one. However, it is of interest to note that the data appear to fit a curved function rather than the linear one predicted by theoretical considerations. The precipitation rate parameter is leveling off or even decreasing at the higher power densities where the value of the rate parameter is in the range of 0.5 to 0.6 ft/sec. This is somewhat higher than the typical average value of 0.4 to 0.5 ft/sec for fly ash precipitators. There may be some level of power input above which a diminishing benefit is derived and other factors such as gas distribution, particle size, rapping losses, electrostatic reentrainment, etc. become the over-riding considerations in precipitator performance. In fact, experimental work[10] with an electrostatic precipitator on high pressure pipeline natural gas containing oil contaminant has shown that at very high electrical field strengths (five to ten times normal), a decrease in the precipitation rate parameter occurs due to electrostatic force reentrainment from the collecting surface.

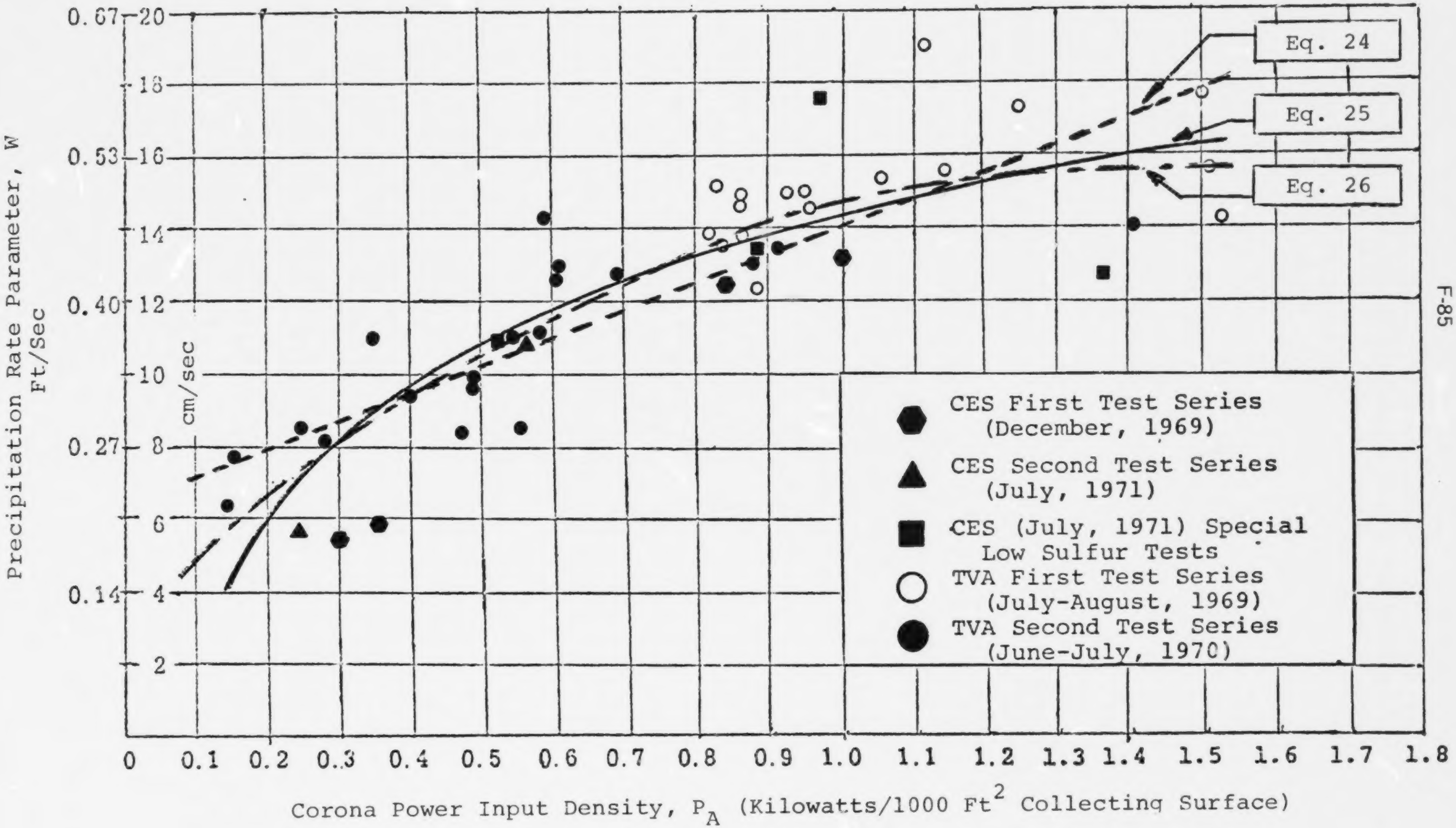


FIGURE 19

PRECIPITATION RATE PARAMETER AS A FUNCTION OF CORONA POWER DENSITY FOR TESTS WITHOUT LIMESTONE INJECTION

Regression analyses of the data (42 sets) using the equation form

$$y = a + bx \qquad (21)$$

$$y = a + b \ln x \qquad (22)$$

$$y = a + bx + cx^2 \qquad (23)$$

where,

y = precipitation rate parameter, W (FPS)

x = corona power input density, P_A (KW/1000 Ft^2)

were performed with a GE Mark I computer. The 4 sets of special low sulfur coal tests, although plotted in Figure 19, have been excluded from the regression analyses.

The following results were obtained:

$$W = 0.21 + 0.25 P_A \qquad (24)$$

Correlation Coefficient = 0.84

F - Ratio Test Statistic = 98

$$W = 0.47 + 0.16 \ln P_A \qquad (25)$$

Correlation Coefficient = 0.87

F = Ratio Test Statistic = 120

$$W = 0.11 + 0.57 P_A - 0.20 P_A^2 \qquad (26)$$

Correlation Coefficient = 0.89

F - Ratio Test Statistic = 75

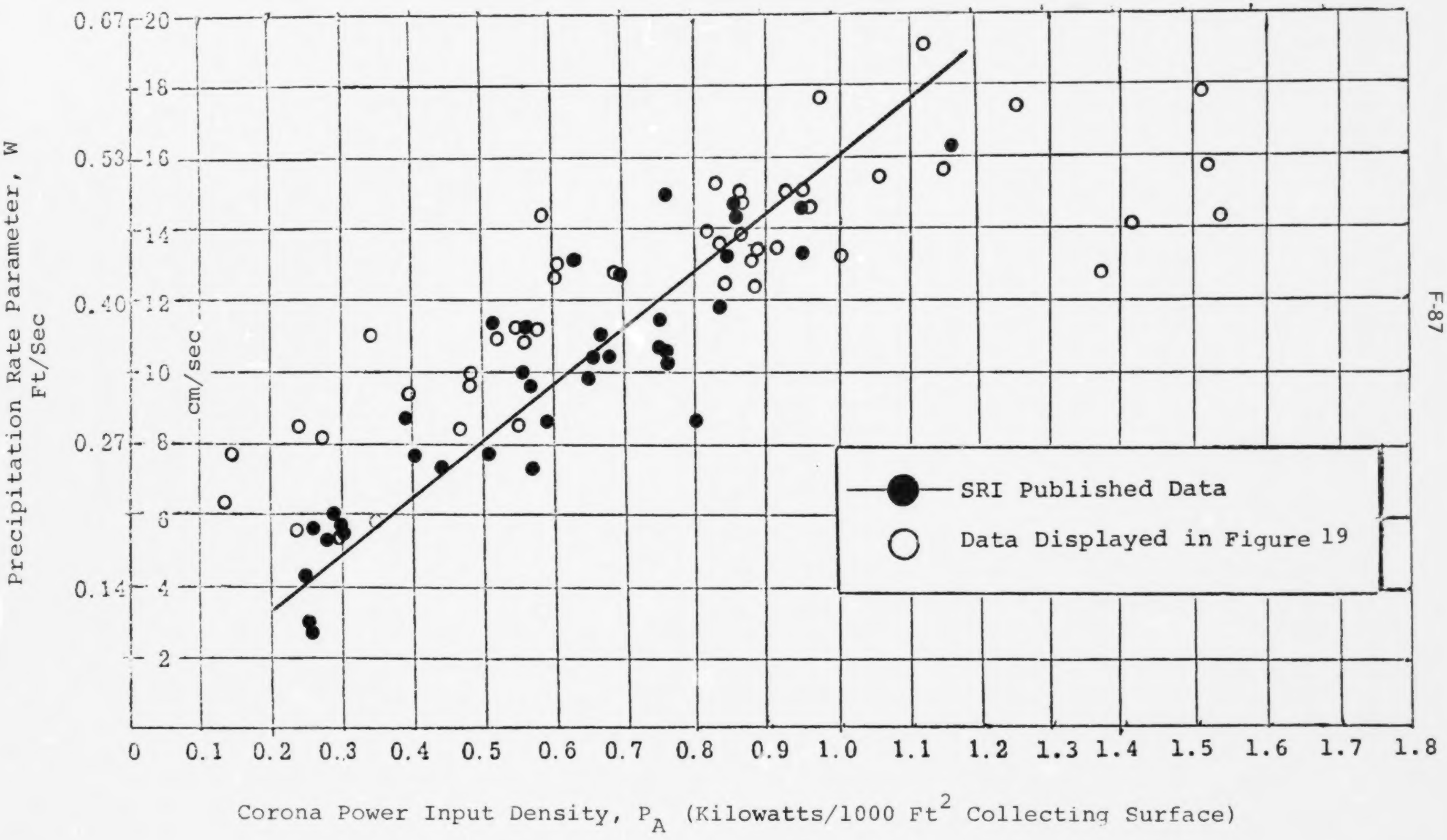
These equations are limited to corona power density data falling in the range of 0.15 to 1.5 kilowatts per 1000 ft^2 of collecting surface which encompasses the normal operating range of fly ash precipitators. All three equations are reasonably good representations of the data with the quadratic form of equation (23) producing the best fit.

Previously published data[11] by Southern Research Institute for a variety of fly ash installations is contained in Figure 20 along with a plot of the data from Figure 19. Although there is considerable scatter in the data points, it is quite apparent that there is a strong relationship between the precipitation rate parameter and the corona power input density. In the range of 0.1 to 1.2 kilowatts/1000 ft^2 of collecting surface, there is fair agreement between the published data and the results of this report. It is postulated that the flue gas temperature and coal sulfur which affect the particulate conductivity are the main parameters causing the data scatter. These variables will be examined in subsequent sections of this report.

Another way of analyzing precipitator performance is to plot the loss in particulate collection efficiency as a semi-logarithmic function of the corona input power expressed as a rate i.e. watts per 1000 actual cubic feet of flue gas per minute. (See equation 19.)

FIGURE 20

COMPARISON OF DATA FROM FIGURE 19 WITH PUBLISHED DATA OF SOUTHERN RESEARCH INSTITUTE FOR VARIOUS FLY ASH PRECIPITATOR INSTALLATIONS REF (11)



The same no limestone injection tests as analyzed above were used for this correlation and the data are plotted in Figure 21. A regression analysis was performed using the form of equation 21 where,

y = ln of the loss in precipitator collection efficiency Q expressed as a fraction

x = precipitator corona input power, P_V (watts/1000 ACFM of flue gas)

The following equation resulted:

$$\ln Q = 1.507 - 0.0138\, P_V \tag{27}$$

Correlation Coefficient = 0.85

F-Ratio Test Statistic = 112

Equation 27 is limited to values of precipitator corona input power rates in the range of 15 to 215 watts per 1000 ACFM of flue gas which encompasses the normal operating range of fly ash precipitators. In Figure 22 the previously published data[11] of Southern Research Institute is plotted along with the results from this report shown in Figure 21. Again the data points are scattered. However, the dependence of precipitator performance on corona power input rate in watts per 1000 ACFM of flue gas treated is obvious. There is fair agreement between the published data and results contained in this report. A resolution of the scatter in data requires a more detailed examination of such variables as gas temperature, coal sulfur, particulate size, gas velocity, rapping mode, etc., which all affect corona power input and precipitator performance. A discussion of these parameters is contained in subsequent sections of this report.

Data from tests with limestone injection (51 sets) are plotted in Figure 23. The 2 sets of special low sulfur coal have been omitted. The precipitation rate parameter W in ft/sec is shown as a function of corona power input density expressed in kilowatts/1000 ft^2 of precipitator collecting surface. Note the maximum level of input power density attainable is about one-half that of the No Limestone injection tests. As discussed previously, the limestone additive has increased the electrical resistivity of the particulate to the extent that the preset optimum sparking rate of the precipitator chosen for the test program, i.e. 50-150 sparks/min is reached at much lower voltage and corona current input resulting in decreased corona power.

Regression analyses of the data presented in Figure 20 using the equations 21, 22, and 23 resulted in the following respectively:

$$W = 0.15 + 0.40\, P_A \tag{28}$$

Correlation Coefficient = 0.68

F-Ratio Test Statistic = 42

FIGURE 21

LOSS IN COLLECTION EFFICIENCY AS A FUNCTION
OF POWER RATE FOR TESTS WITHOUT LIMESTONE INJECTION

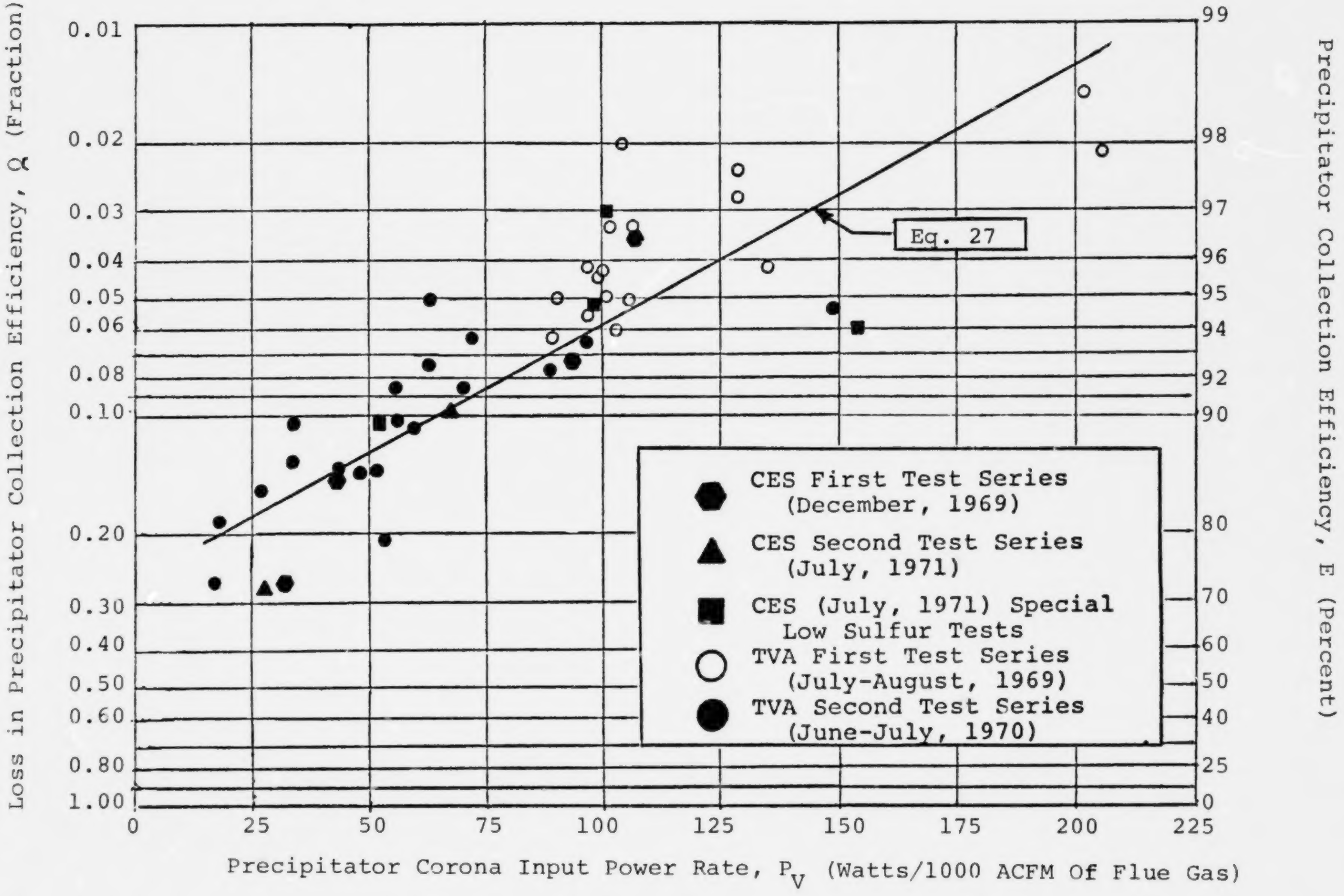
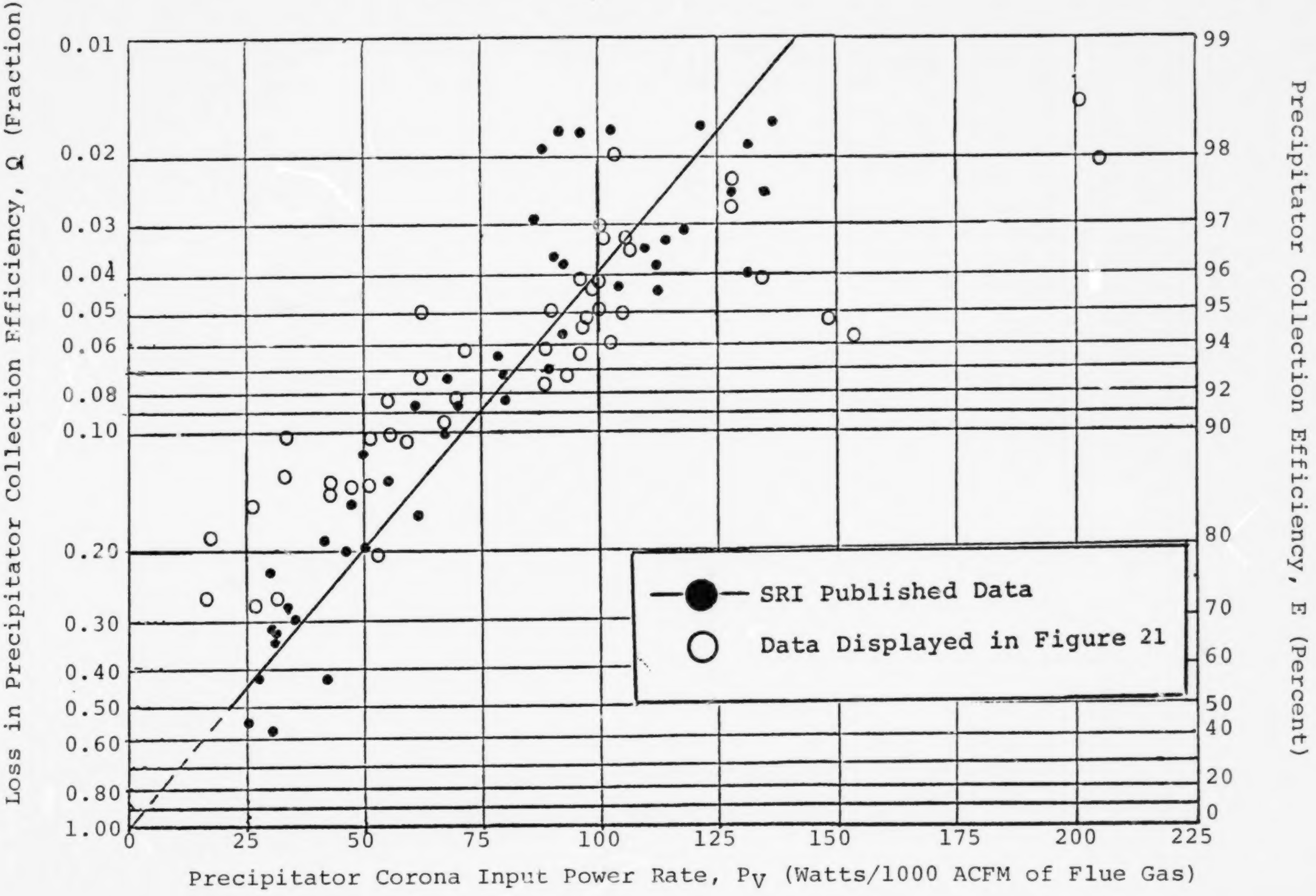


FIGURE 22

COMPARISON OF DATA FROM FIGURE 21 WITH PUBLISHED DATA OF SOUTHERN RESEARCH INSTITUTE FOR VARIOUS FLY ASH PRECIPITATOR INSTALLATIONS - REF. (11)



$$W = 0.42 + 0.11 \ln P_A \tag{29}$$

Correlation Coefficient = 0.73

F-Ratio Test Statistic = 55

$$W = 0.10 + 0.78 P_A - 0.54 P_A^2 \tag{30}$$

Correlation Coefficient = 0.71

F-Ratio Test Statistic = 24

These equations are limited to a corona power density range of 0.05 to 0.7 kilowatts/1000 Ft^2 of precipitator collecting surface, which although quite low, are typical values for a precipitator collecting high resistivity particulate. All three equations give equally significant data representations with the semi-logarithmic form of equation 22 giving a slightly better correlation. The data points from Figure 19 (No Limestone injection) are plotted on Figure 23 for comparison. In general, it appears that for equal corona power input densities there is no significant difference in the precipitation rate parameter whether limestone is injected or not. However, it should be reiterated that the maximum level of corona power input density attainable and the resultant precipitator performance is significantly lower with limestone injection. In Figure 24 the loss in precipitator particulate collection for the No Limestone injection tests is plotted as a semi-logarithmic function of the corona input power expressed as a rate (watts per 1000 actual cubic feet of flue gas per minute).

A regression analysis of the No Limestone injection data shown in Figure 24 was performed using the form of equation 21. The following result was obtained:

$$\ln Q = 0.868 - 0.026 P_V \tag{31}$$

Correlation Coefficient = 0.66

F-Ratio Test Statistic = 43

Equation 31 is limited to precipitator corona input power rates of 5 to 80 watts per 1000 ACFM of flue gas which is the lower range of normal fly ash precipitator operation but still typical when high resistivity ash is encountered.

The No Limestone injection data from Figure 21 are also plotted on Figure 24 for comparison. In comparable ranges of corona power input rates, there is fair correlation of data regardless whether limestone is injected or not. However, the rates attainable with No Limestone injection are much higher resulting in increased performance.

The test data with limestone injection are more scattered than the No Limestone injection data, but still show the strong dependence of precipitator performance on corona power input.

FIGURE 23

PRECIPITATION RATE PARAMETER AS A FUNCTION OF CORONA POWER DENSITY FOR TESTS WITH LIMESTONE INJECTION

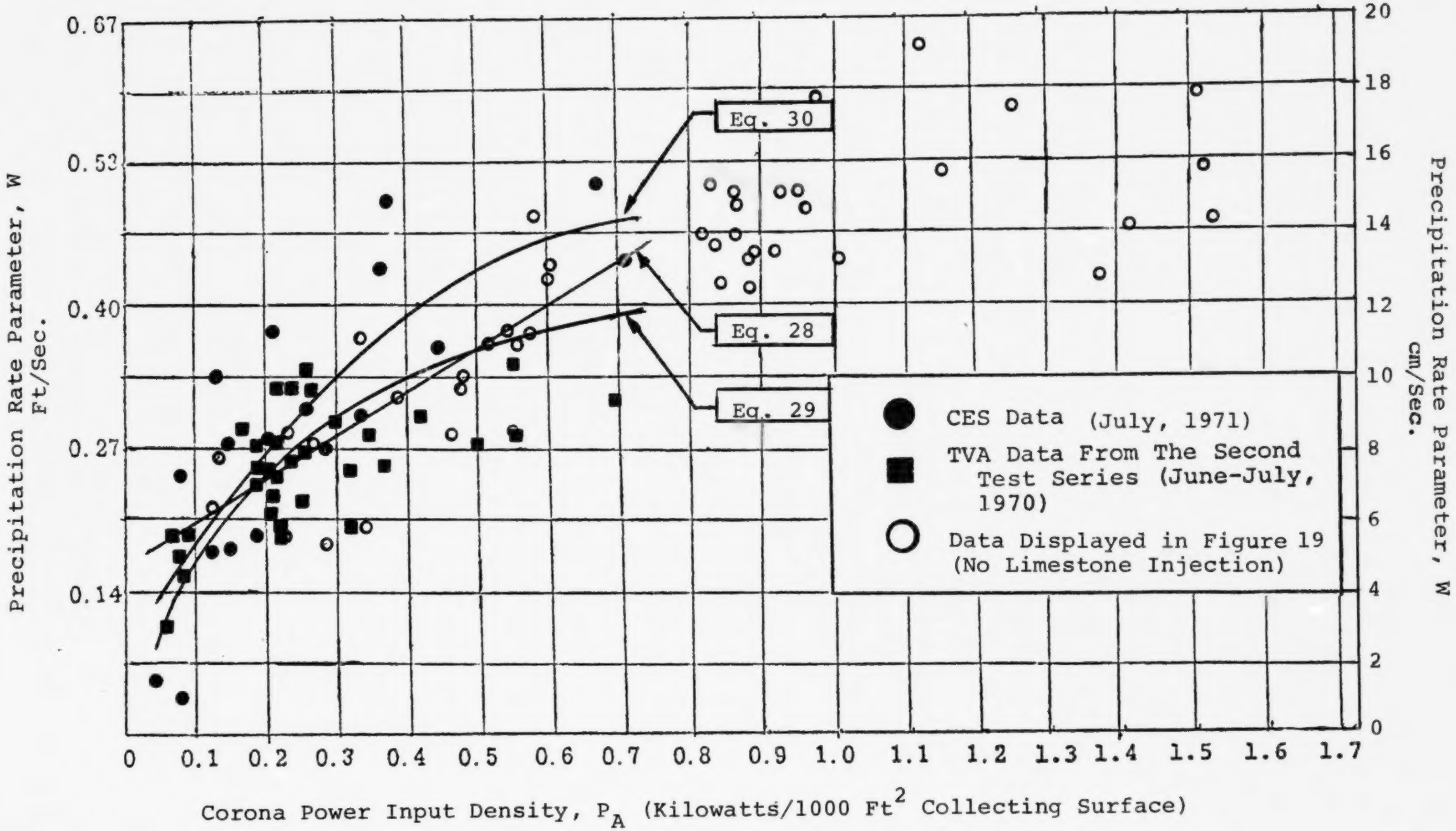
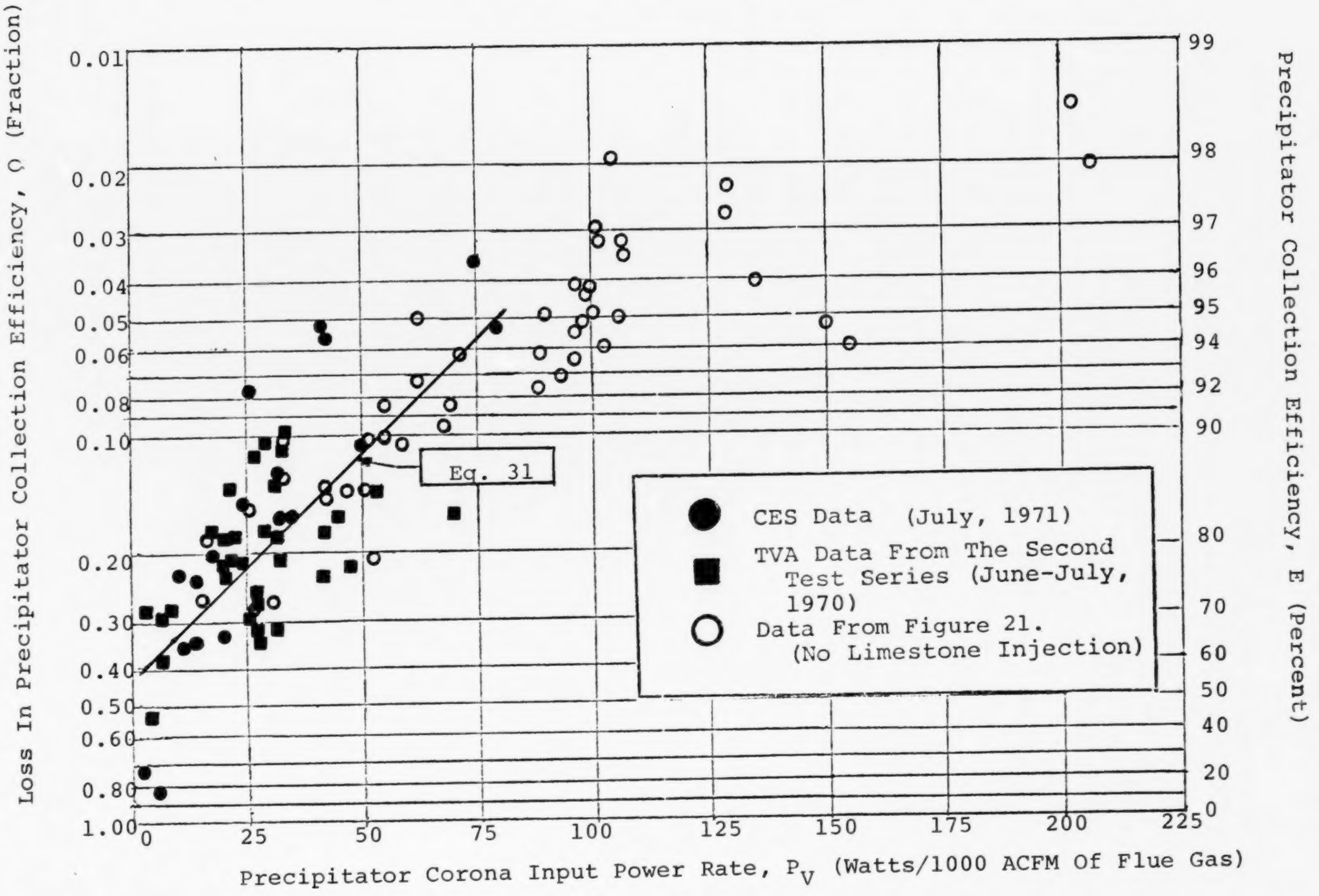


FIGURE 24

LOSS IN COLLECTION EFFICIENCY AS A FUNCTION OF POWER RATE FOR TESTS WITH LIMESTONE INJECTION



C. Correlation of Precipitator Corona Power Input With Process Variables

In order to make the results of the test program more useful for predicting precipitator performance and sizing with limestone injection, a more detailed analysis has been made using only the test results from the Cottrell Environmental System's second test series (July 1971) in which a statistically designed experiment investigated four variables at two levels, i.e. limestone particle size, flue gas temperature coal sulfur and limestone to sulfur stoichiometry. Other variables such as precipitator sparking rate and rapping mode were held essentially constant. The four variables have been correlated with corona power input density which in turn allows estimating the precipitation rate parameter from Figure 25 with subsequent sizing of the electrostatic precipitator for any gas volume and collection efficiency specified. A summary of pertinent data used for this analysis is contained in Table XXX. In Figure 25, the precipitation rate and corona power input data (Table XXX) have been plotted so as to be able to identify the injected limestone particle size and flue gas temperature for each point. Note that the coarse limestone injection generally resulted in higher precipitation rates at equivalent corona power input, and the lower gas temperatures allowed increased corona power input. (As indicated earlier, this latter result can be explained on the basis of lower particulate resistivity at the decreased gas temperature resulting in higher voltage and corona current input before the preset spark limitation). Using the form of Equation 22, a separate regression analysis on the coarse and fine limestone test results was performed involving 7 and 11 sets of data, respectively.

The following equations were obtained:

(Coarse) $W = 0.522 + 0.121 \ln P_A$ (32)
Correlation Coefficient = 0.80
F-Ratio Test Statistic = 16

(Fine) $W = 0.46 + 0.136 \ln P_A$ (33)
Correlation Coefficient = 0.81
F-Ratio Test Statistic = 9

Equations 32 and 33 are limited to values of precipitator corona input power densities in the range of 0.05 to 0.70 kilowatts per 1000 Ft^2 of collecting surface. The coarse and fine limestone particle size distributions from randomly selected tests (Table XXX) are shown in Figure 26. Separate regression analyses on coarse and fine limestone injection correlating the corona input power density to the four process variables tested were performed. (See Table XXX for data used). From theoretical considerations and past operational experience, expectations were that the corona power input would vary directly with the amount of sulfur in the coal, and inversely with the amount of limestone injected and the gas temperature (range 240 to about 325 F).

FIGURE 25

PRECIPITATION RATE PARAMETER AS A FUNCTION OF CORONA POWER DENSITY FOR TESTS WITH LIMESTONE INJECTION

(GAS TEMPERATURE AND LIMESTONE PARTICLE SIZE ARE IDENTIFIED SEPARATELY)

(Data Points From Table XXX)

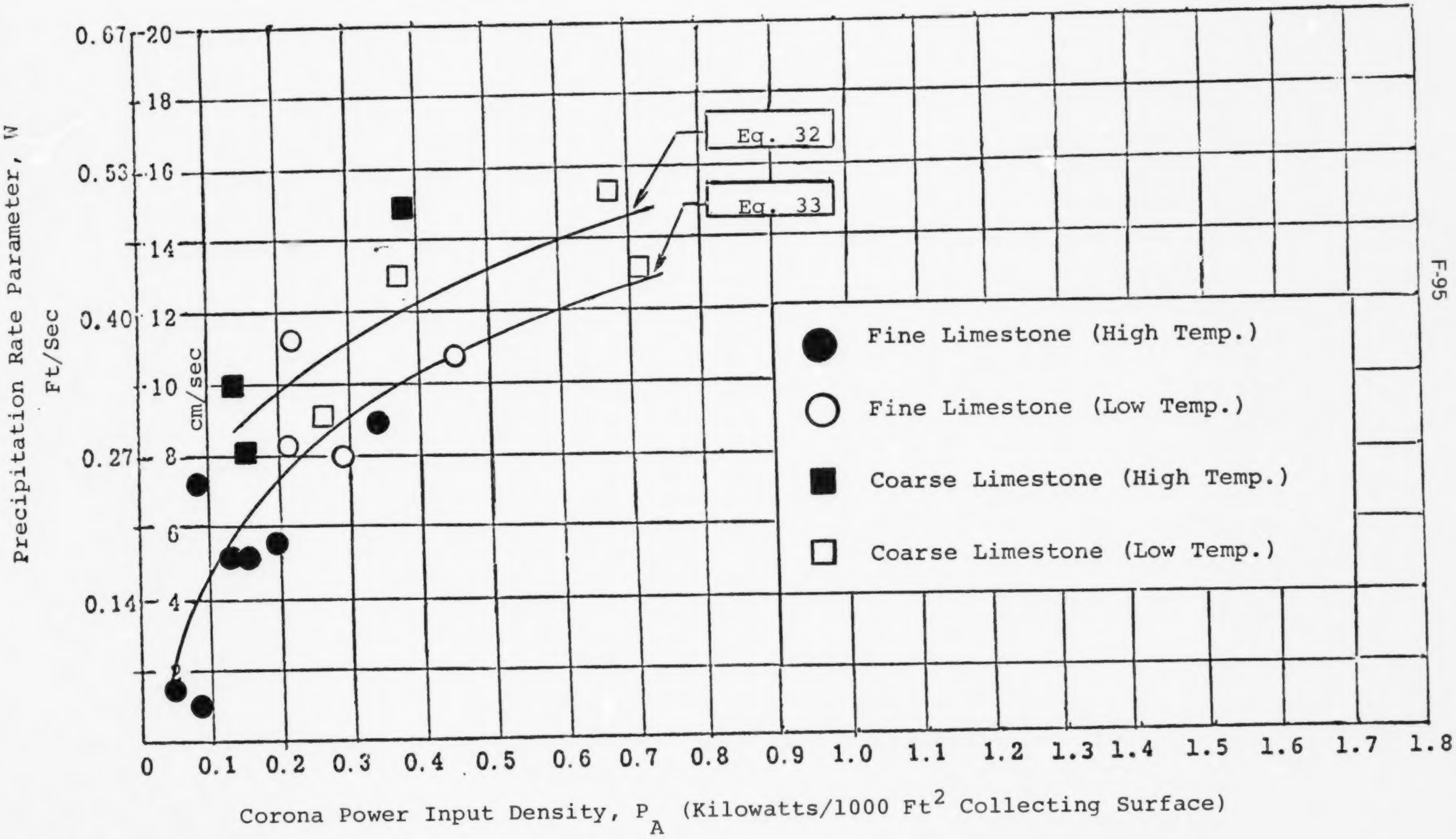


TABLE XXX

SUMMARY OF TEST DATA USED IN CORRELATIONS

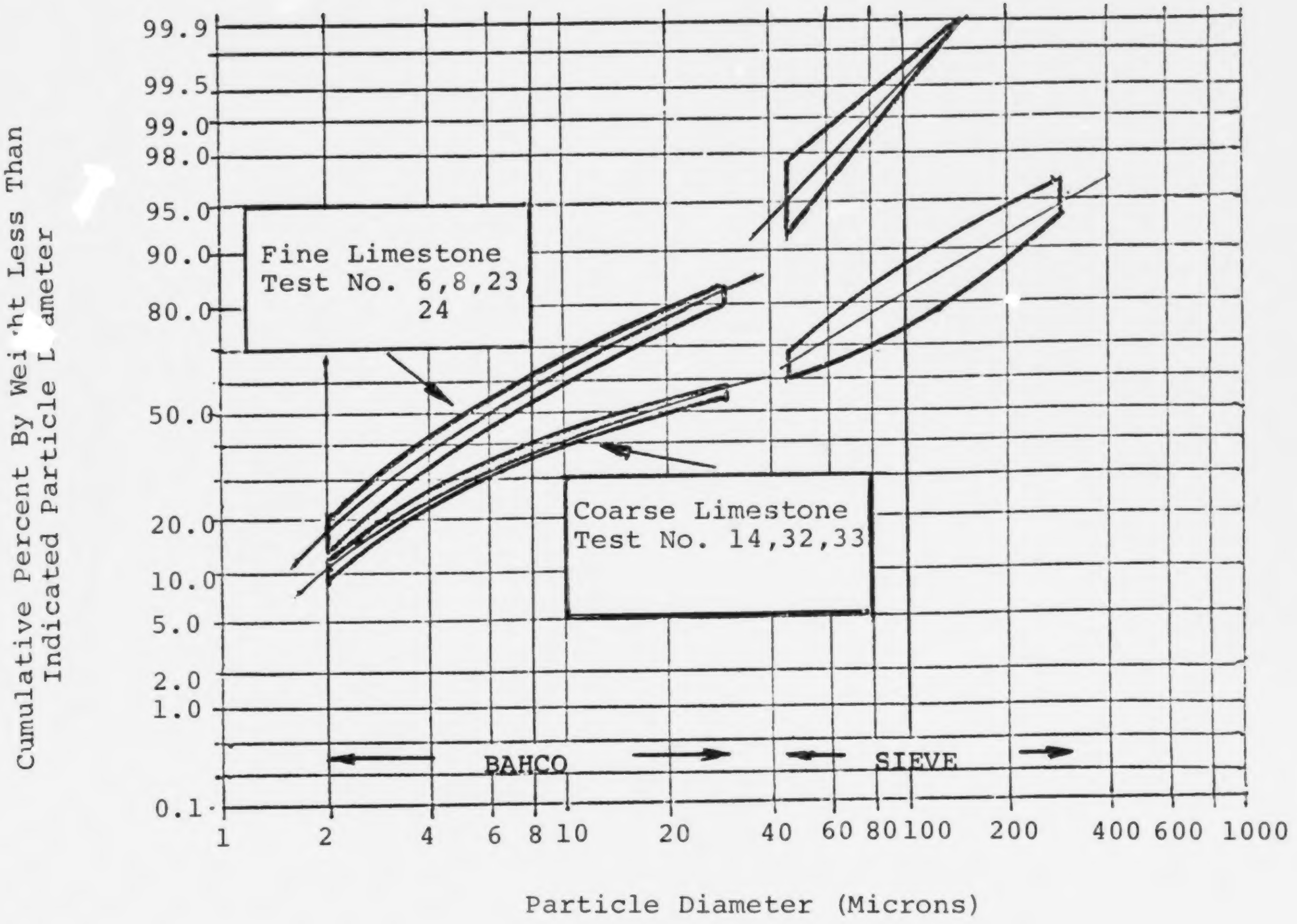
(CES Limestone Injection Tests, July 1971)

Test No.	Flue Gas Temp., °F	Limestone Particle Size	Limestone Ton/Hr Feed	Sulfur Ton/Hr Fired	Stoichiometry CaO/SO_2 (3)	Precipitation Rate Parameter FPS	Power Density $Watts/Ft^2$
2	314	F (1)	7.55	1.47	1.44	0.24	0.093
4	305	F	9.50	0.99	2.69	0.06	0.057
6	301	F	11.60	1.79	1.81	0.03	0.096
8	256	F	11.15	1.63	1.92	0.35	0.460
10	251	C (2)	16.75	1.08	4.34	0.43	0.372
11	290	C	15.25	1.11	3.85	0.26	0.164
14	289	C	14.10	1.60	2.47	0.33	0.139
15	244	C	14.45	1.39	2.91	0.29	0.275
17	243	F	9.70	0.93	2.92	0.37	0.220
18	289	F	9.15	1.25	2.05	0.17	0.112
25	253	C	10.55	1.25	2.36	0.50	0.674
26	289	F	7.05	1.31	1.51	0.17	0.129
27	242	F	6.45	1.07	1.69	0.26	0.296
28	290	F	11.15	2.04	1.53	0.29	0.334
29	241	F	6.25	1.43	1.22	0.27	0.213
30	288	F	5.30	1.67	0.89	0.18	0.199
32	289	C	8.50	1.85	1.29	0.48	0.396
33	241	C	7.85	2.28	0.96	0.43	0.708

(1) F - Fine (80%-400 Mesh)
(2) C - Coarse (50%-400 Mesh)
(3) Assumes limestone is 100% $CaCO_3$ and all sulfur in the coal appears in the flue gas as SO_2

FIGURE 26

PARTICLE SIZE ANALYSES OF LIMESTONE FEED SAMPLES
USED IN SECOND CES TEST SERIES



The following equation form was used for the analyses:

$$Y = a + bx_1 + \frac{c}{x_2} + \frac{d}{x_3} \qquad (34)$$

where,

y = precipitator corona power input density, P_A (kilowatts/1000 Ft^2 collecting surface)
x_1 = coal sulfur fires, S (tons/hr)
x_2 = limestone injected, L (tons/hr)
x_3 = flue gas temperature, T ($^\circ$F x 10^{-2})

The resultant equations were:

(Coarse)
$$P_A = -1.435 - 0.336S + \frac{10.0}{L} + \frac{3.87}{T} \qquad (35)$$

Correlation Coefficient = 0.96
F-Ratio Test Statistic = 12

(Fine)
$$P_A = -0.990 + .199S - \frac{0.694}{L} + \frac{2.74}{T} \qquad (36)$$

Correlation Coefficient = 0.83
F-Ratio Test Statistic = 5

Equations 35 and 36 are limited to the following ranges representing actual test conditions which are realistic in practice:

Coal Sulfur Fired (S)	1.0 to 3.2 tons/hr
Limestone Feedrate (L)	5.3 to 16.8 tons/hr
Flue Gas Temperature (T)	(240 to 315) (10^{-2}) °F
Stoichiometry 0.28 (L/S)	1.0 to 4.0

The ratio of limestone feedrate (L) to coal sulfur fired (S) is a function of stoichiometry and if the assumption is made that the limestone is 100% $CaCO_3$ and all the coal sulfur fired appears in the flue gas as sulfur oxides, the following relationship is established:

$$\text{Stoichiometry } \frac{CaO}{SO_2} = 0.28\frac{L}{S} \qquad (37)$$

By using equations 32, 33, 35, and 36 it is possible to predict precipitator corona power input and performance with limestone injection based on the process variables of limestone size, injection rate, coal sulfur and flue gas temperature provided the equation limitations indicated are met.

2. Performance of the Combination Mechanical-Electrostatic Dust Collector

The dust collecting equipment on Shawnee, Boiler No. 10 (see Figure 2) is a combination multitube mechanical followed by an electrostatic precipitator. In early years, when 90% collection efficiency was satisfactory, the economics were against combination units. However, demands for high efficiency changed this, resulting in utilization of combination unit principles where advantageous, as discussed below.

> Technical advantages cited for the combination unit are the complementary effects, e.g. mechanical efficiency drops off with lower gas throughput while precipitator efficiency increases with higher collecting area to volume ratios. Conversely, mechanical efficiency increases with high throughput while precipitator performance decreases. Furthermore, grit collection is more readily done with a mechanical while fine particulate is more effectively removed with a precipitator. With a combination unit, electrical failure of the precipitator or other outage still permits some collection with a mechanical. Removal of grit particulate ahead of the precipitator can reduce erosion losses. A multiple tube mechanical preceding the electrostatic in a close couple will also improve gas distribution as well as reduce the dust loading allowing the use of a smaller precipitator.
>
> Disadvantages of the combination unit are the high draft loss of the mechanical collector which represents a higher operating cost (typically, about 0.25 KW per thousand CFM per inch of draft loss), and also higher capital costs for fans, flues, etc. With mechanical collectors as primary units, discharge electrode rappers are a necessity and plate rapping may also be more difficult because of compaction of the finer dust. Abrasion and plugging of the mechanical tubes can be a consideration.

In the present case where dry limestone is injected into the boiler for sulfur oxide removal, all the technical advantages cited above are favored and the use of a combination collector is desirable, particularly in the case of coarse limestone.

A. Correlation of Particle Size and Dust Collector Performance

The most important parameters in determining the performance of a mechanical collector are dust particle size and specific gravity. Normally, maximum performance is obtained when pressure loss across the collector is between 2.5 and 4 inches of water. On the other hand, the electrical properties of the dust and level of applied electrical power are critical parameters in an electrostatic precipitator with particle size of lesser importance.

A critique of particle size as it is related to dust collector performance on Shawnee Boiler No. 10 follows:

A plot of the particle size analyses contained in Table XIX through XXII are shown graphically in Figures 26 through 43.

Figure 26 shows particle size distributions of the raw limestone feed for both the coarse and fine grinds. Note that the grind was very uniform with the fine having a geometric mean size by weight of about 6 microns and the coarse 17 microns.

Size distributions for fly ash obtained during no limestone injection tests (both CES test series) are shown in Figures 27 through 33. Figures 34 through 43 present particle size distributions of samples taken during the limestone injection runs (second CES test series).

Using the average distribution curves from the above figures, fractional efficiency curves were calculated for both the mechanical and electrostatic collectors. Differences in size distribution between inlet, outlet and hopper catch samples served as a basis for these calculations. The results for no limestone injection are contained in Table XXXI and for limestone injection in Tables XXXII and XXXIII. For comparative purposes the collector fractional efficiency curves are shown in Figures 44 and 45. Mechanical collector efficiencies on fly ash alone ranged from about 25% on the 5 micron size to 90 to 95% on greater than 25 microns. However, the electrostatic collector fractional efficiency was nearly constant, i.e. between 80 and 90% over the entire size range. In general, the mechanical efficiencies on fly ash plus additive reaction products is about the same as on fly ash alone or perhaps a little lower. However, the electrostatic collector results show higher efficiency for collection of the fines with efficiency decreasing as the particle size increases. It is postulated that the generally lower precipitator power densities achievable in the limestone injection tests in combination with high dust resistivity and increased sparking have reentrained the larger particles more easily than the fines which tend to stick to the plates once collected.

Further confirmation of this premise is evident in Figure 45 where the fractional efficiency on coarse material for coarse limestone injection is markedly higher than for fine limestone. This can be logically explained by the fact that, in general, higher levels of corona power input density were attainable with the coarse injection and therefore higher electrical forces were available for holding material on the precipitator collecting surface.

Table XXXIV summarizes the geometric mean sizes and specific gravities of all particle size analyses on samples from both Cottrell Environmental Systems test series. The fly ash at the mechanical inlet for all no limestone injection tests had an average mean size

FIGURE 27

PARTICLE SIZE ANALYSES OF MECHANICAL COLLECTOR INLET SAMPLES WITHOUT LIMESTONE INJECTION (TESTS 1A,1B,3A,4A,5A,5B)

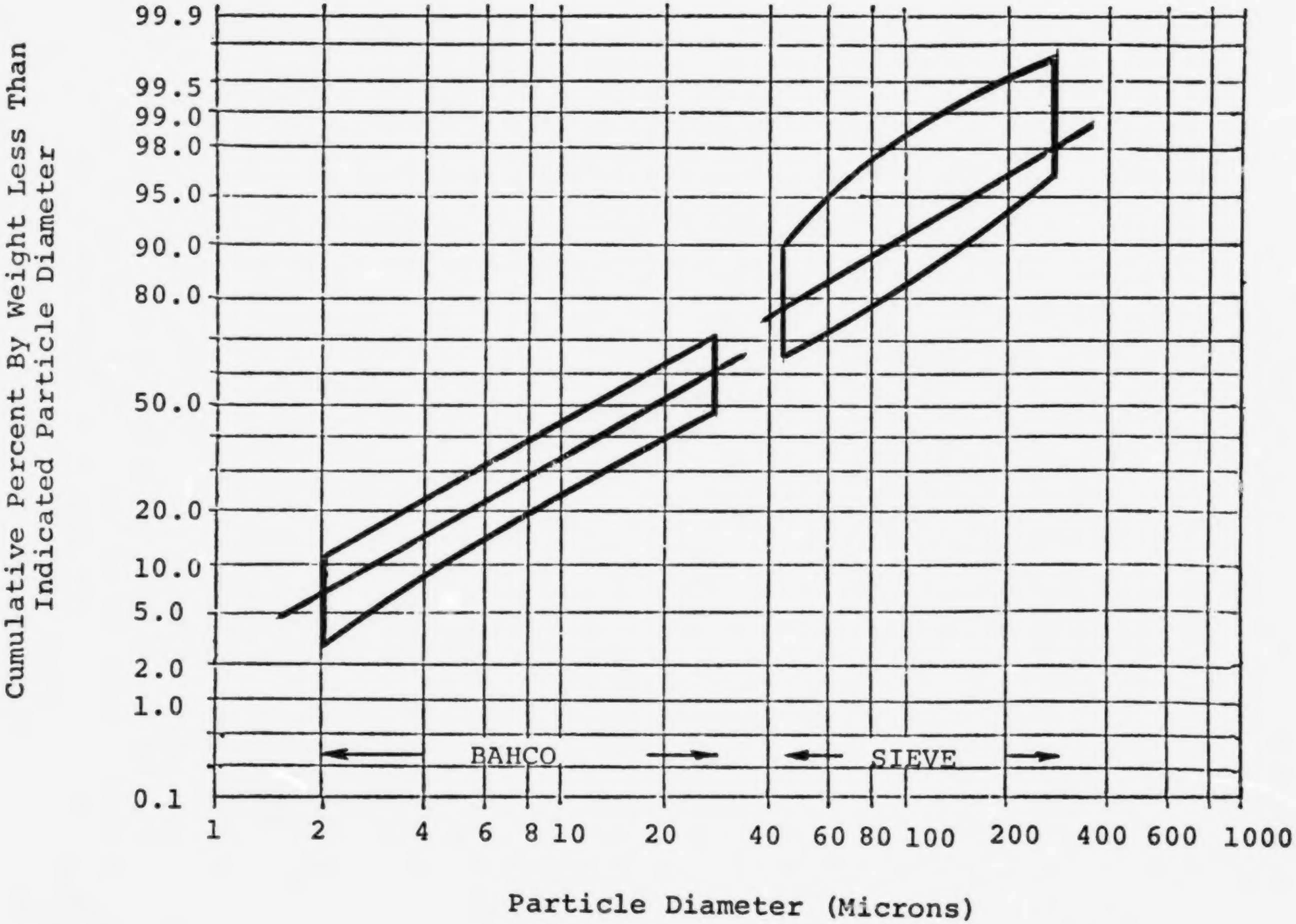


FIGURE 28

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR INLET SAMPLES WITHOUT LIMESTONE INJECTION (TESTS 3A,4A,4B,5A,5B)

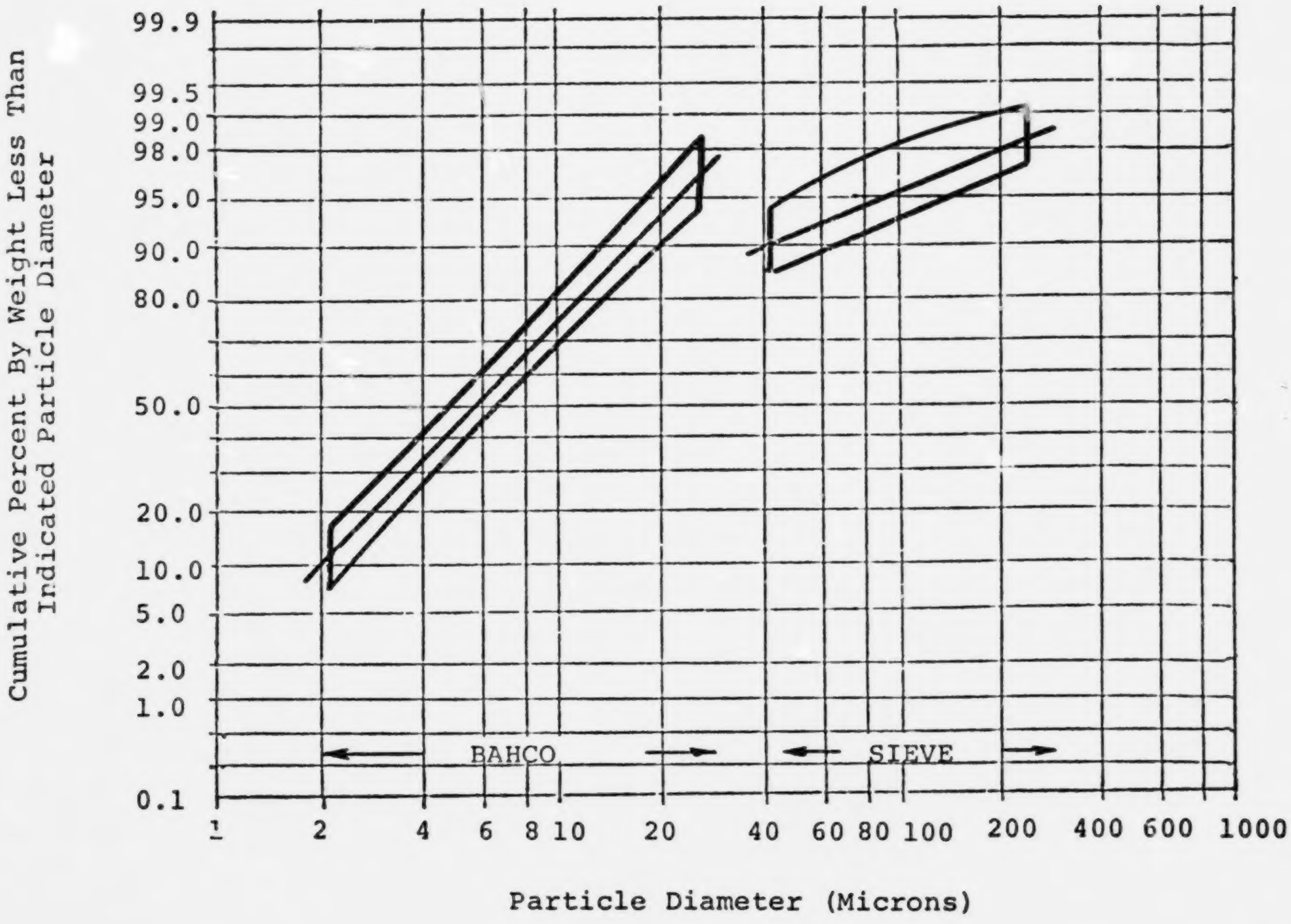


FIGURE 29

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR

OUTLET SAMPLES WITHOUT LIMESTONE INJECTION (TESTS 2A,3A,3B,4B)

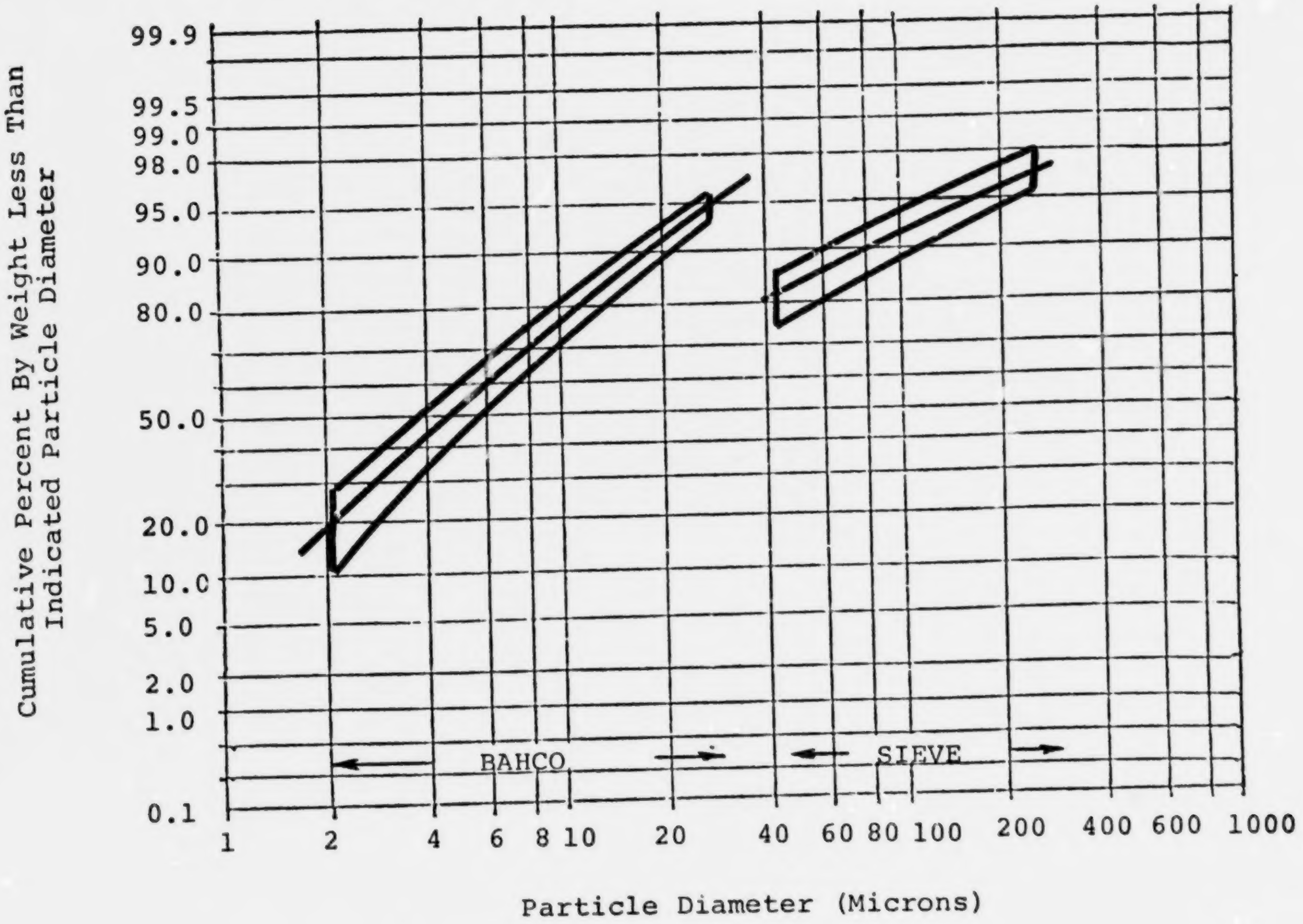


FIGURE 30

PARTICLE SIZE ANALYSES OF MECHANICAL HOPPER SAMPLES WITHOUT LIMESTONE INJECTION

(TESTS 1A,1B,2A,3A,3B,4A,4B,5A,5B)

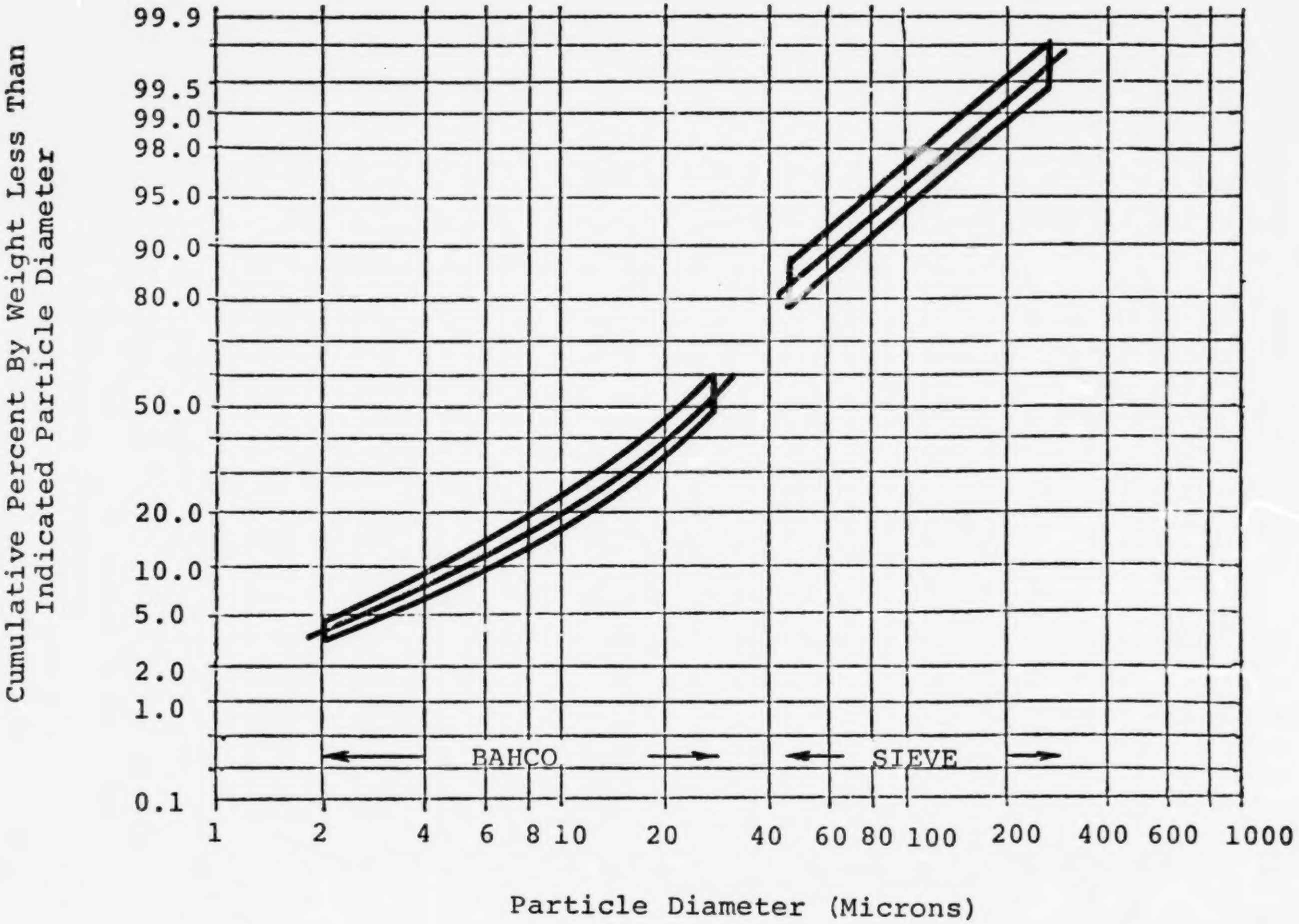


FIGURE 31

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR HOPPER SAMPLES WITHOUT LIMESTONE INJECTION

(TESTS 1A,1B,2A,3A,4A,5A,5B)

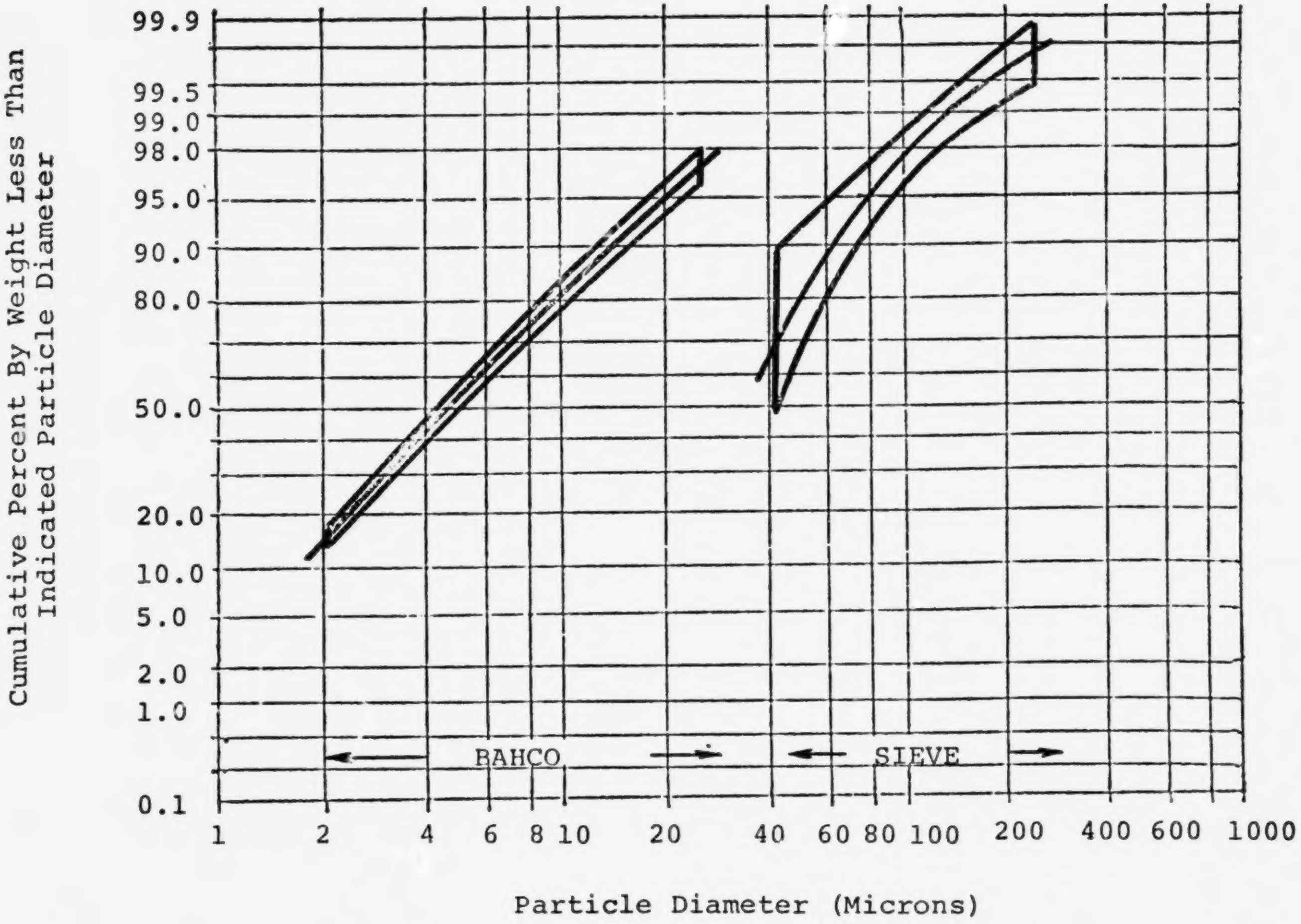


FIGURE 32

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR INLET SAMPLES

WITHOUT LIMESTONE INJECTION (TESTS 16,19,20,21,22)

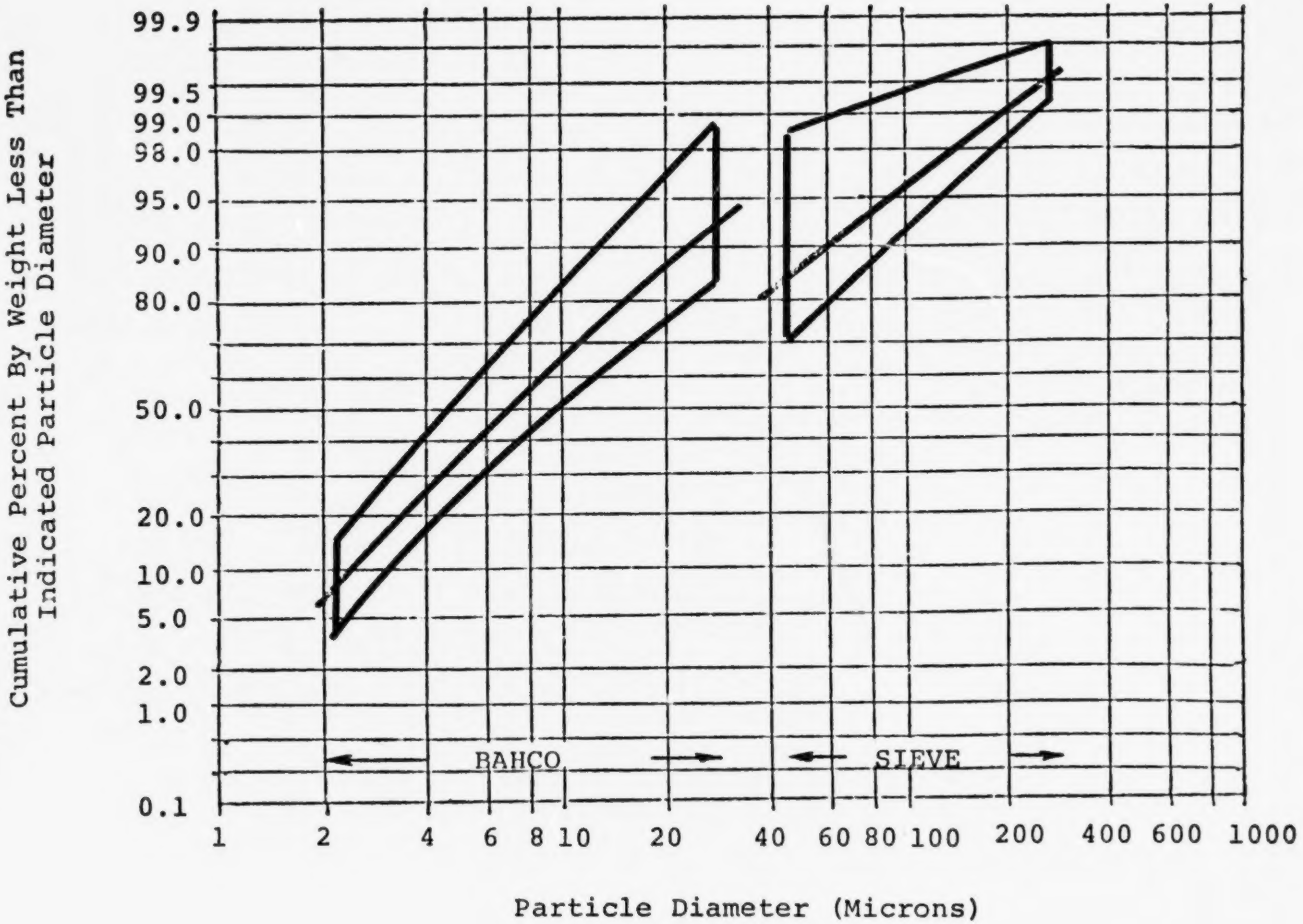


FIGURE 33

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR HOPPER SAMPLES

WITHOUT LIMESTONE INJECTION (TESTS 16,21,22)

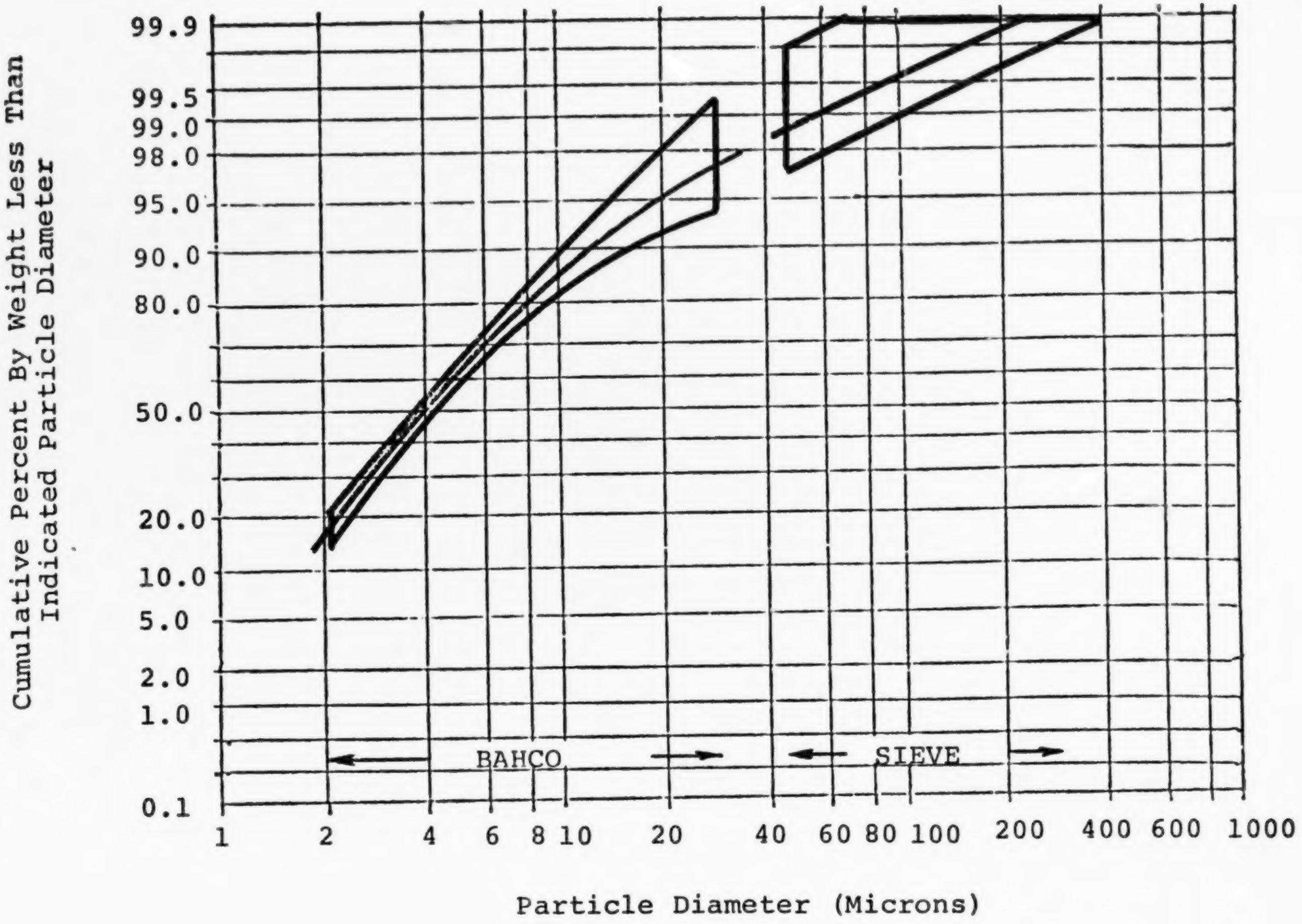


FIGURE 34

PARTICLE SIZE ANALYSES MECHANICAL COLLECTOR INLET SAMPLES
WITH COARSE LIMESTONE INJECTION (TESTS 14,15,32,33)

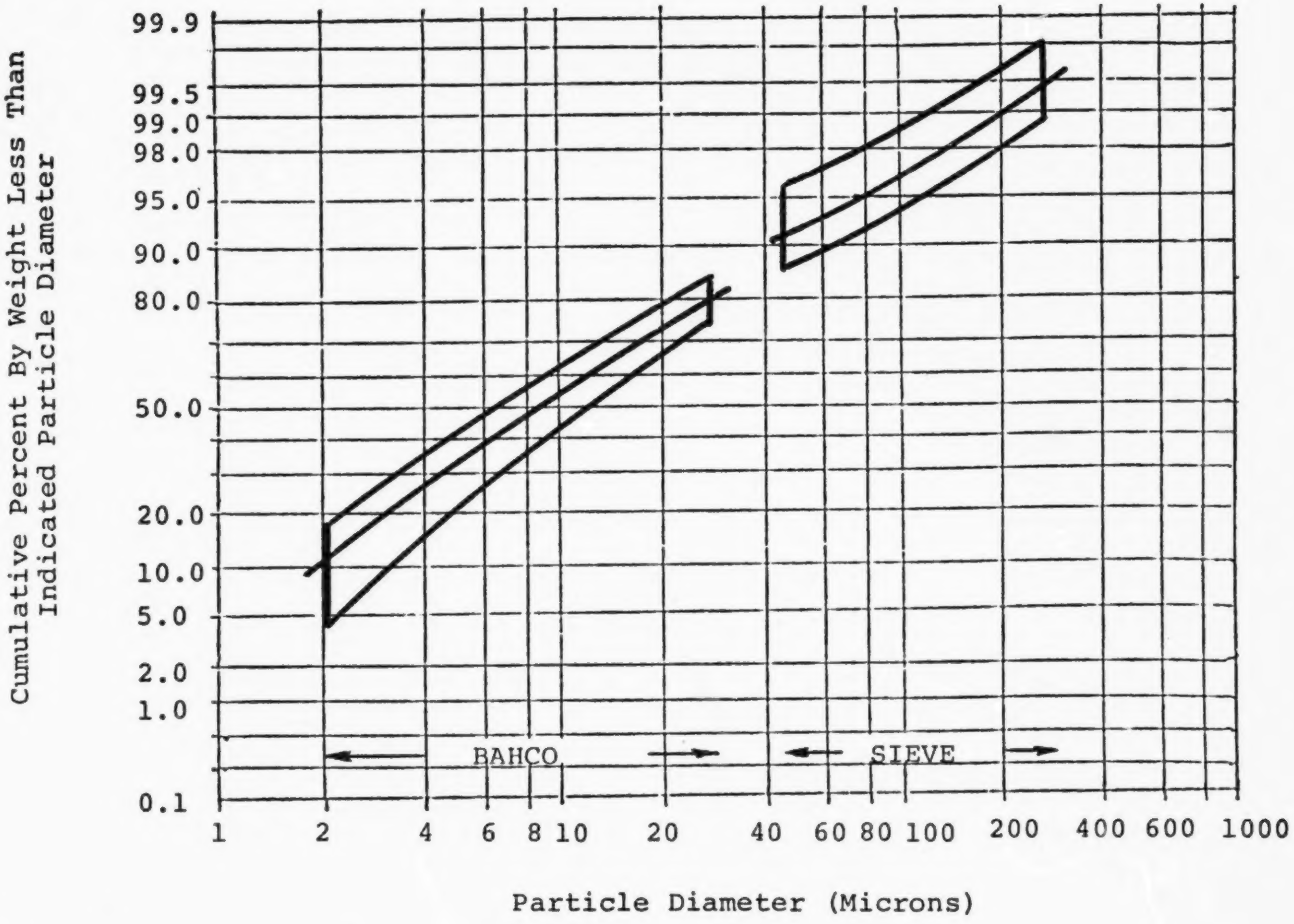


FIGURE 35

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR INLET SAMPLES WITH COARSE LIMESTONE INJECTION (TESTS 10,11,14,15,25,32,33)

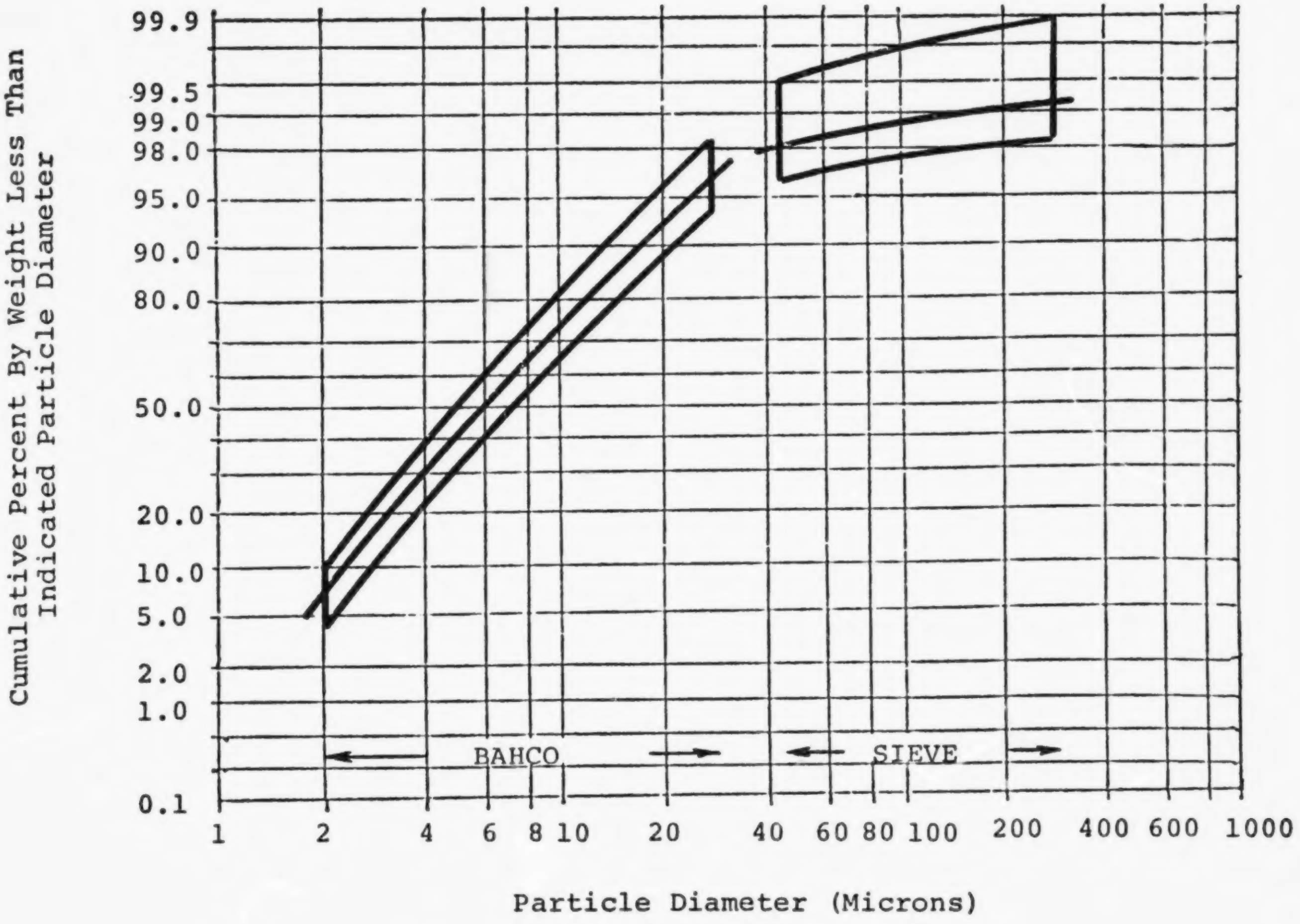


FIGURE 36

PARTICLE SIZE ANALYSIS OF ELECTROSTATIC PRECIPITATOR OUTLET SAMPLES WITH COARSE LIMESTONE INJECTION (TESTS 11,14)

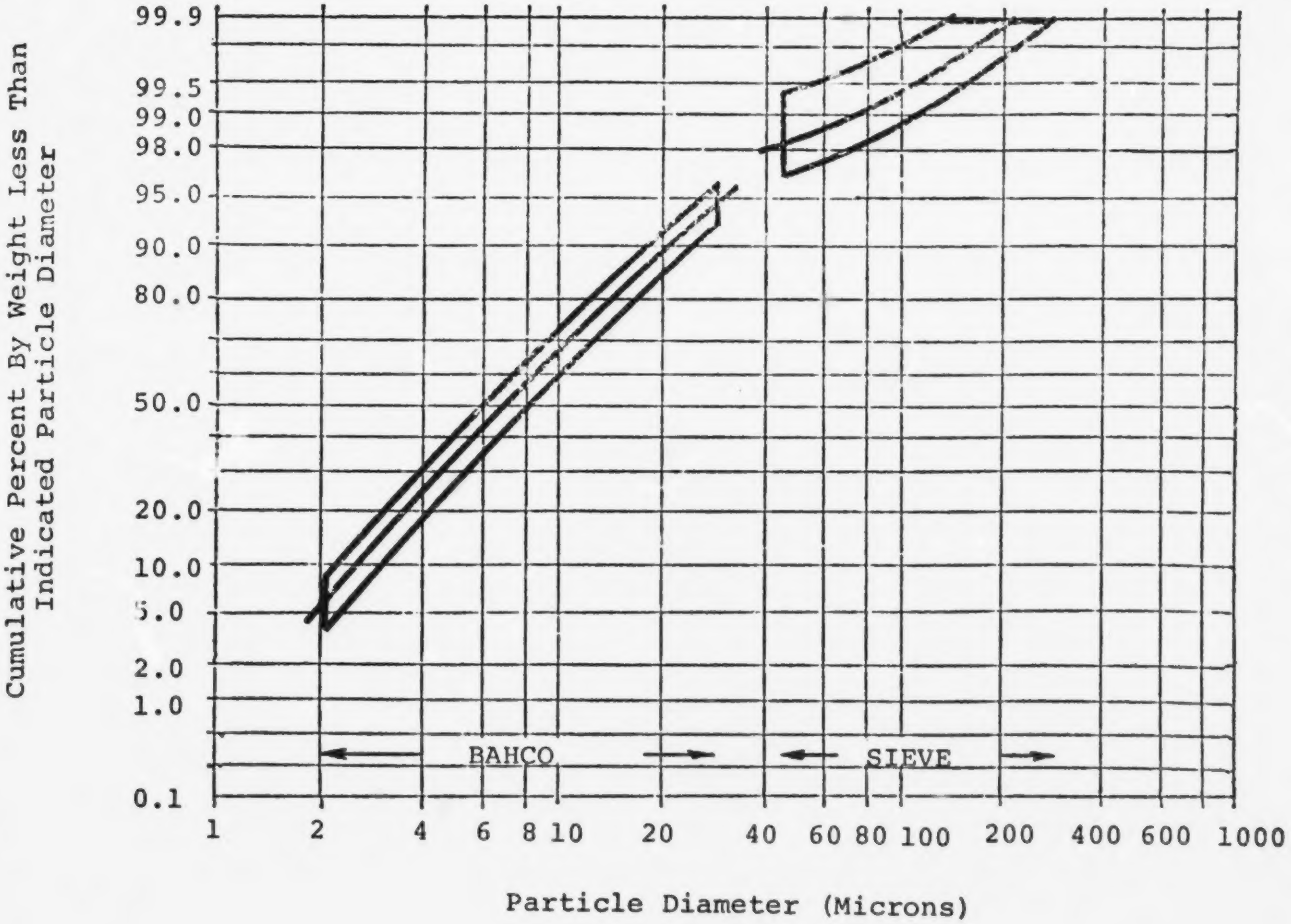


FIGURE 37

PARTICLE SIZE ANALYSES OF MECHANICAL COLLECTOR HOPPER SAMPLES WITH COARSE LIMESTONE INJECTION (TESTS 14,15,32,33)

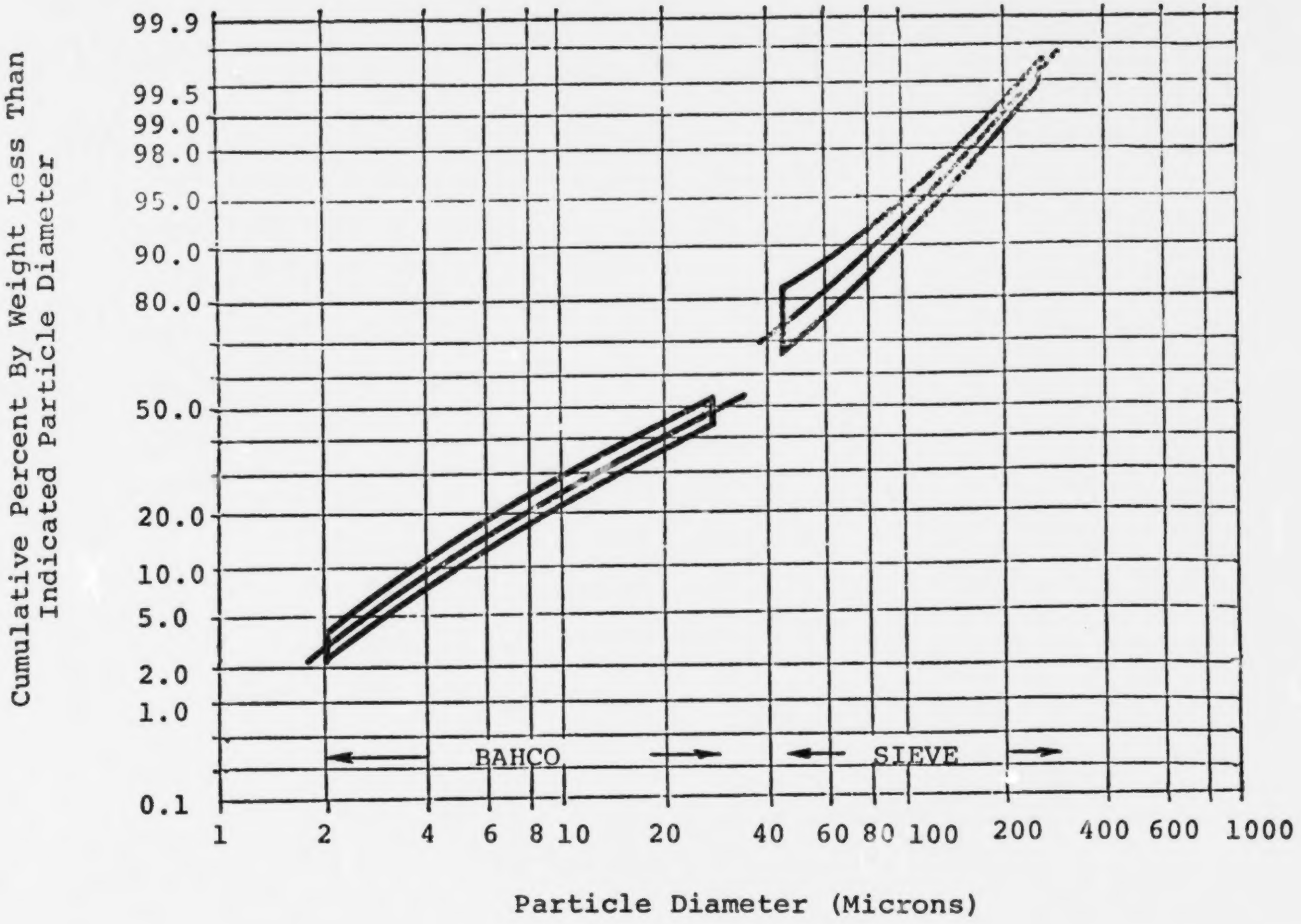


FIGURE 38

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR HOPPER SAMPLES
WITH COARSE LIMESTONE INJECTION (TESTS 14,15)

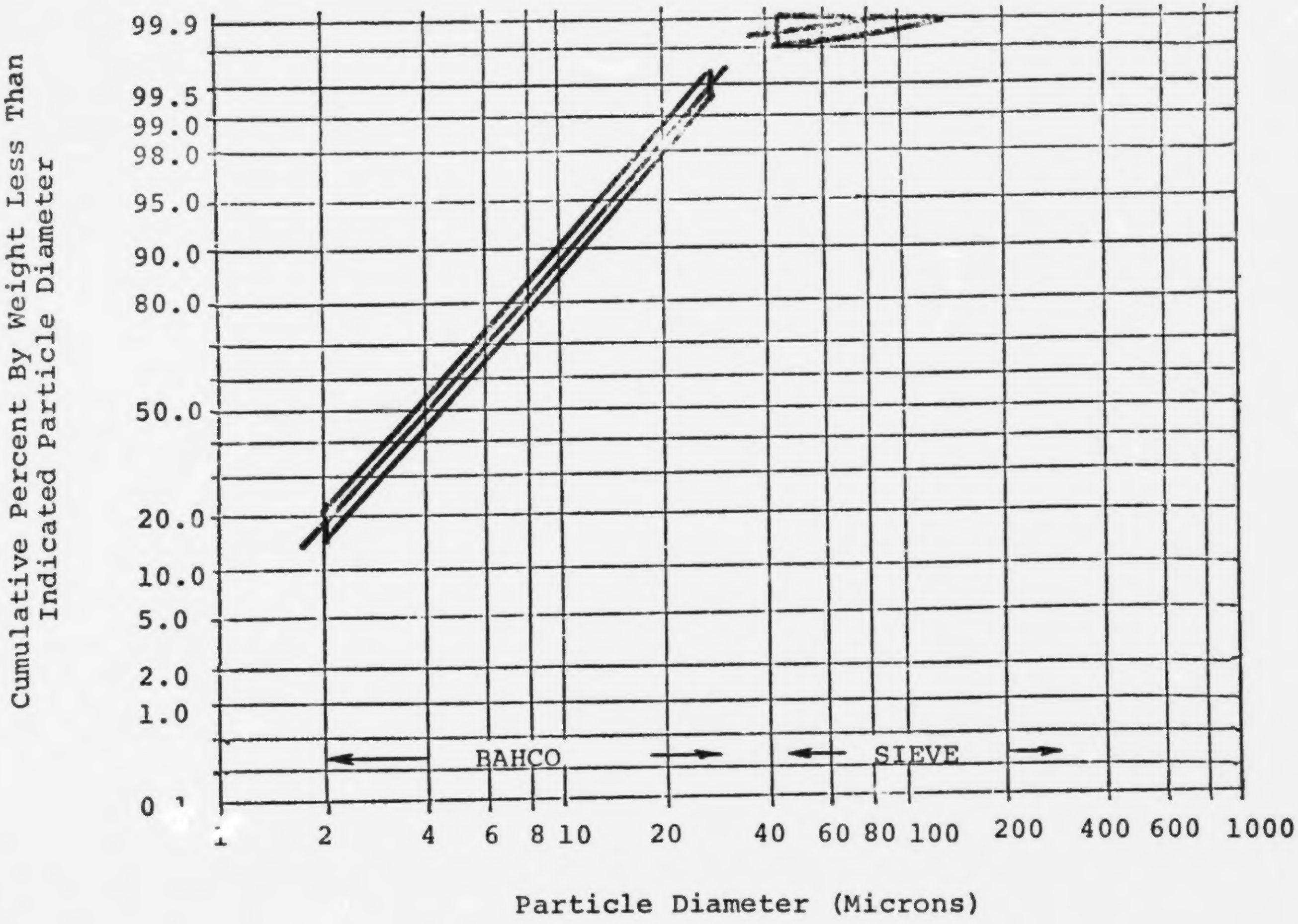


FIGURE 39

PARTICLE SIZE ANALYSES OF MECHANICAL COLLECTOR INLET SAMPLES WITH FINE LIMESTONE INJECTION (TESTS 2,3,5,6,8)

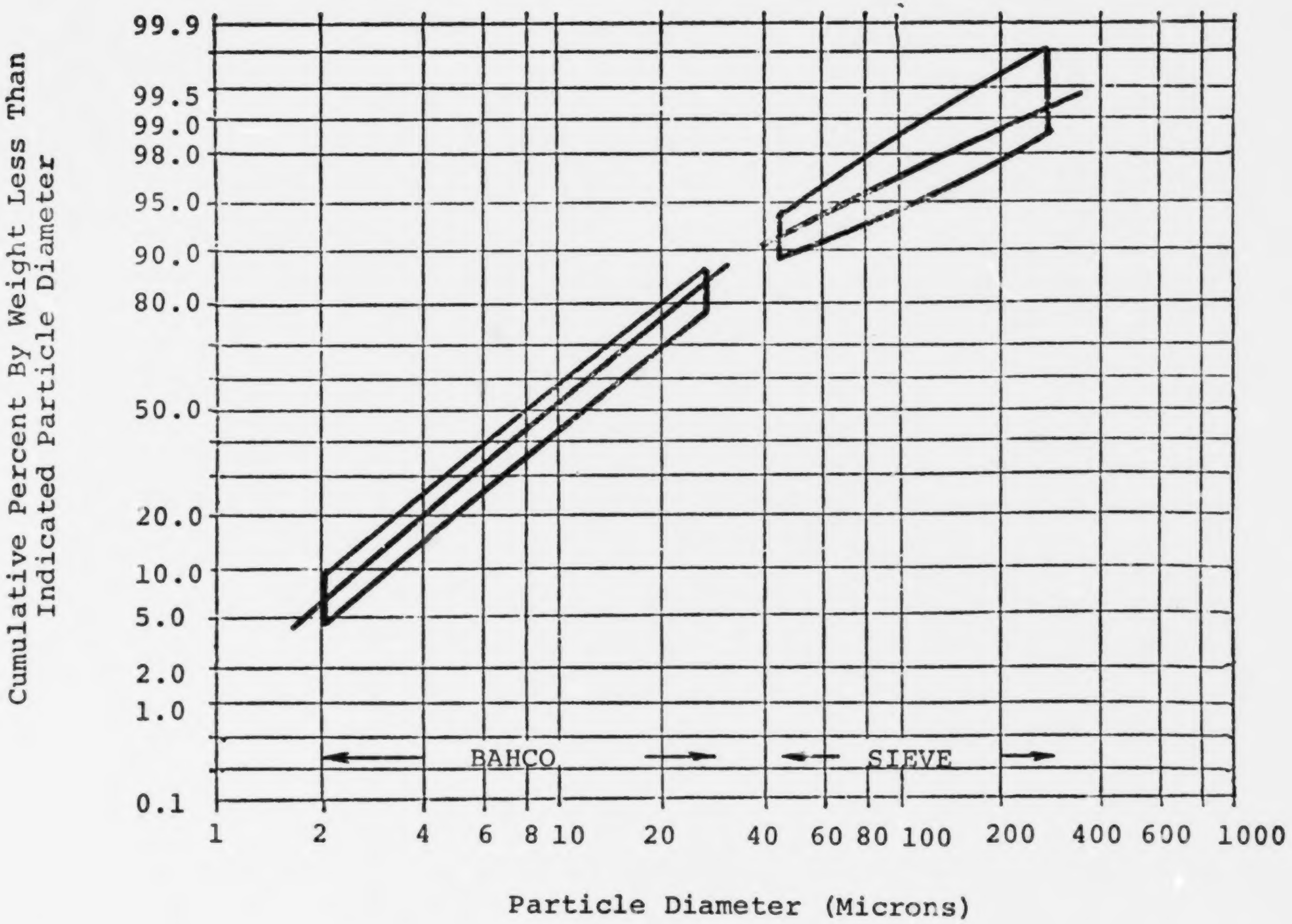


FIGURE 40

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR INLET SAMPLES WITH FINE LIMESTONE INJECTION (TESTS 2,3,4,5,6,8,17,18,23,24,26,27,28,29,30)

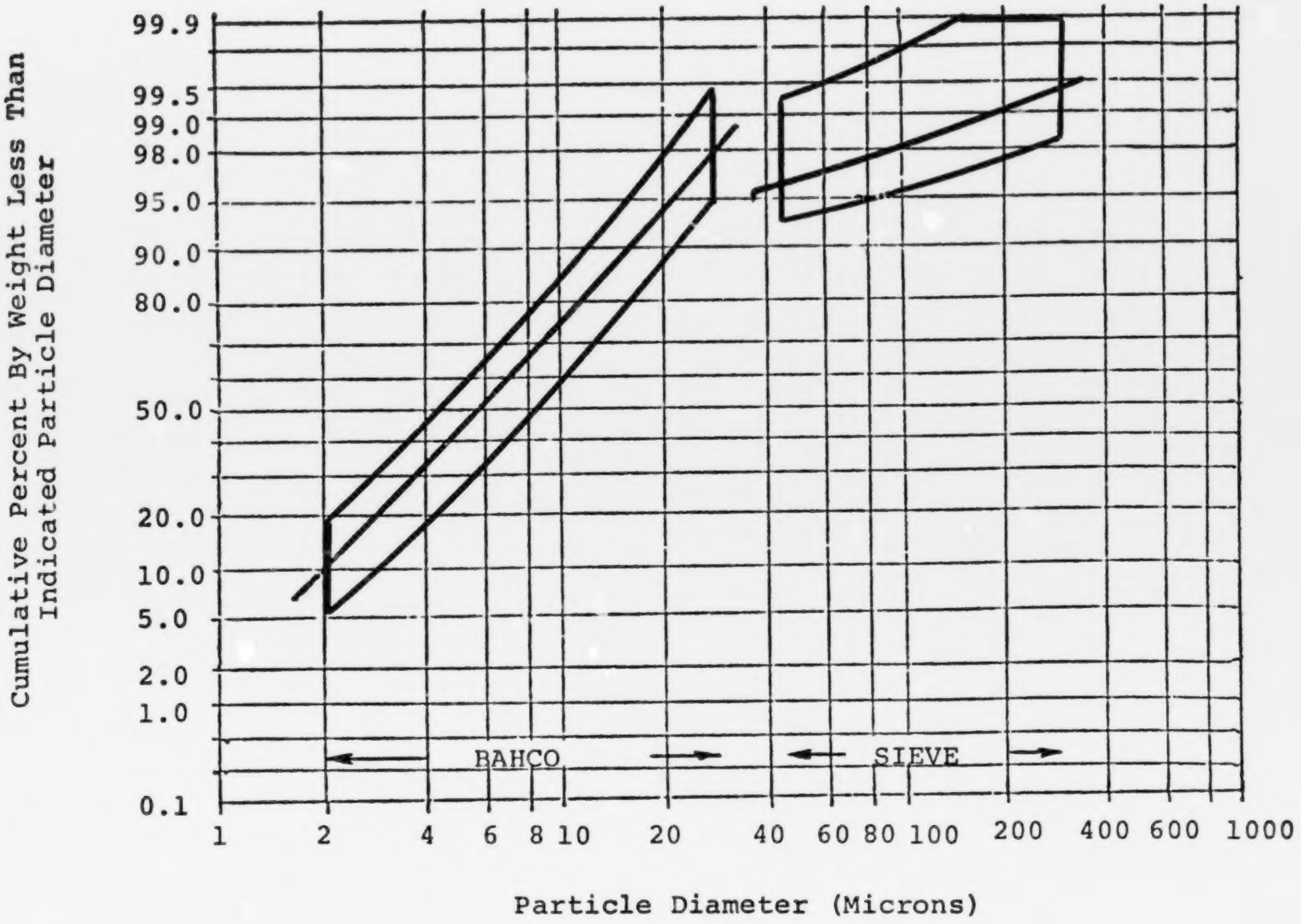


FIGURE 41

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR OUTLET SAMPLES WITH FINE LIMESTONE INJECTION (TESTS 2,3,4,5,6,23,24,26)

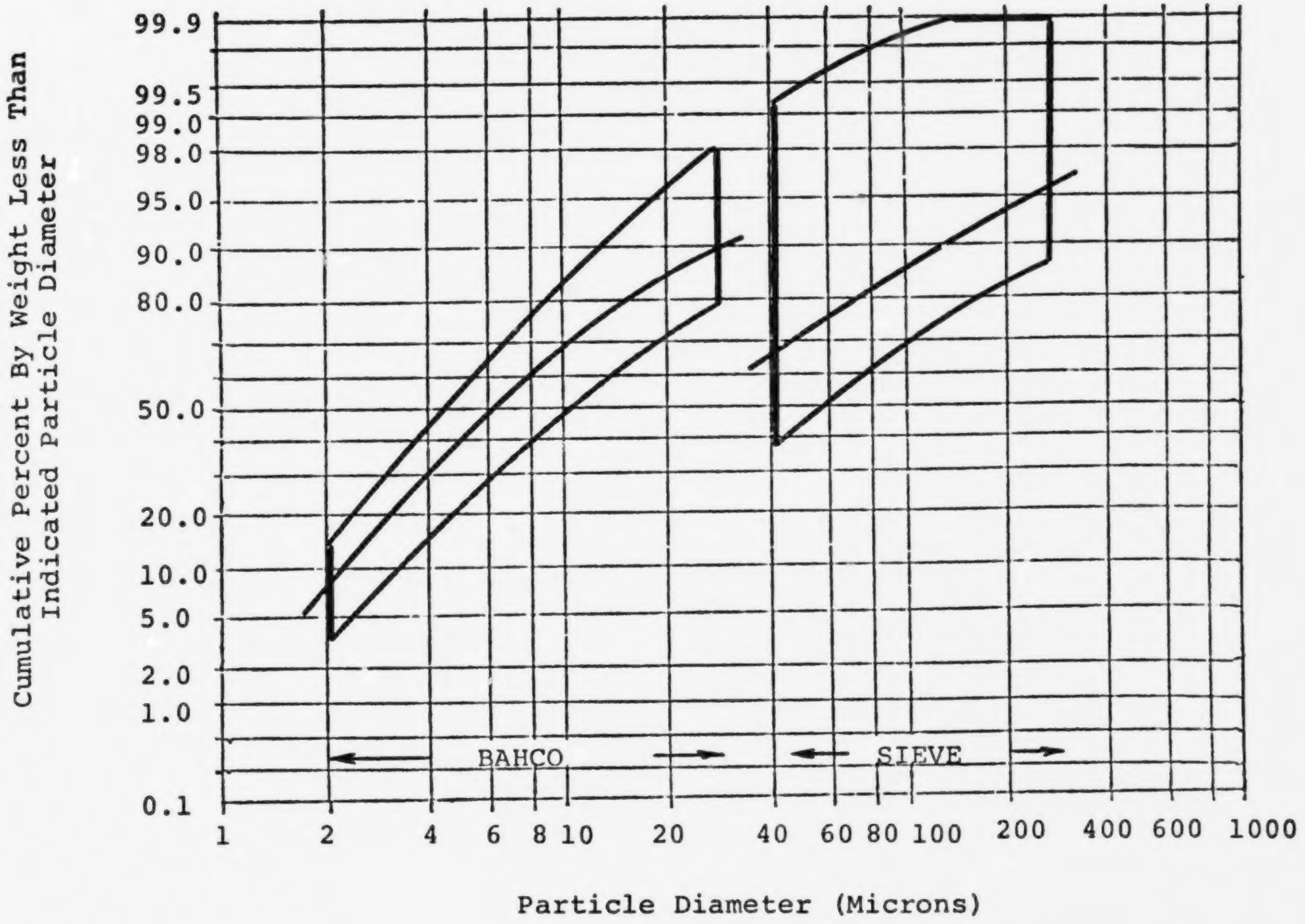


FIGURE 42

PARTICLE SIZE ANALYSES OF MECHANICAL COLLECTOR HOPPER SAMPLES
WITH FINE LIMESTONE INJECTION (TESTS 2,3,5,6,8)

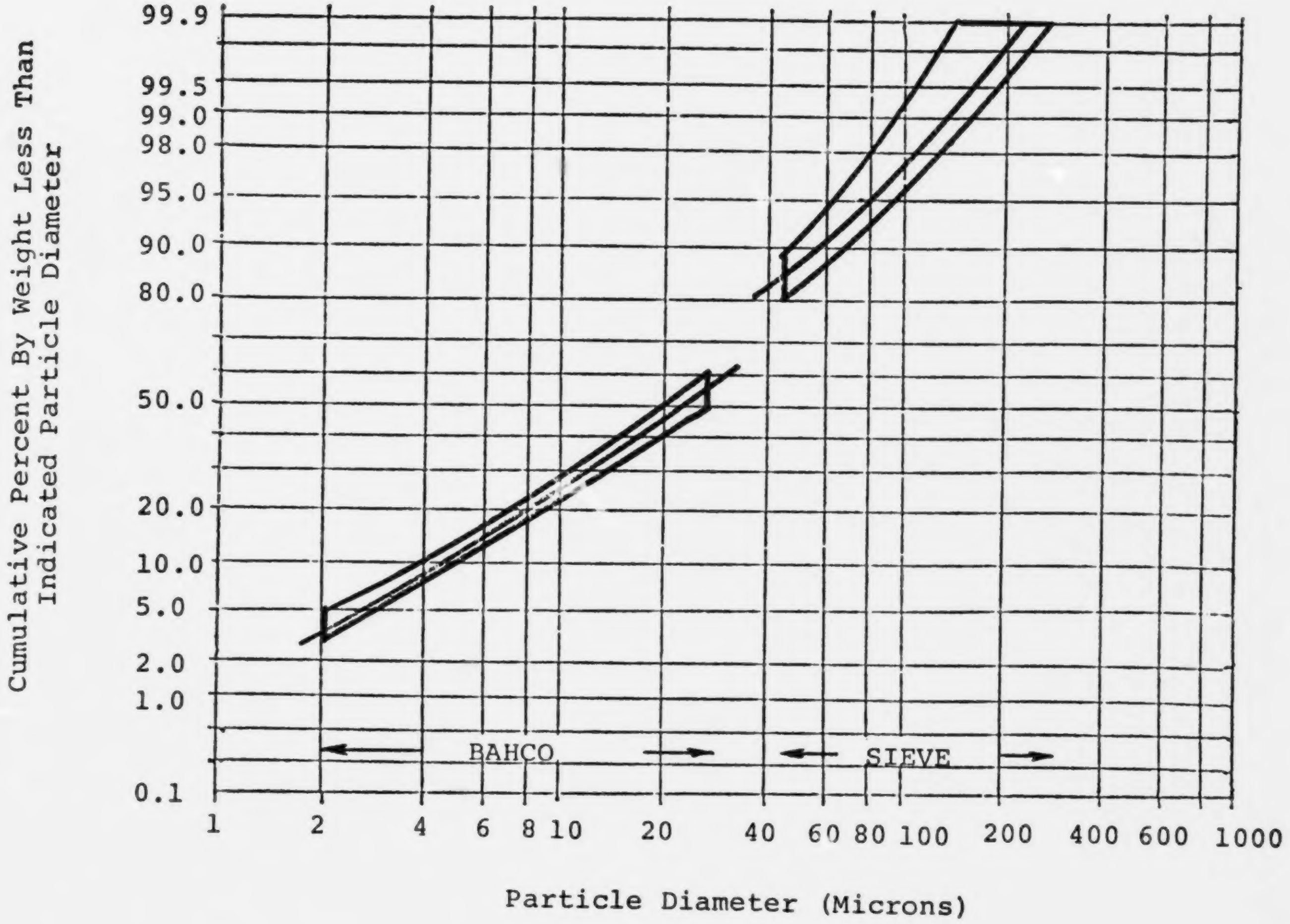


FIGURE 43

PARTICLE SIZE ANALYSES OF ELECTROSTATIC PRECIPITATOR HOPPER SAMPLES

WITH FINE LIMESTONE INJECTION (TESTS 17,18,23,24)

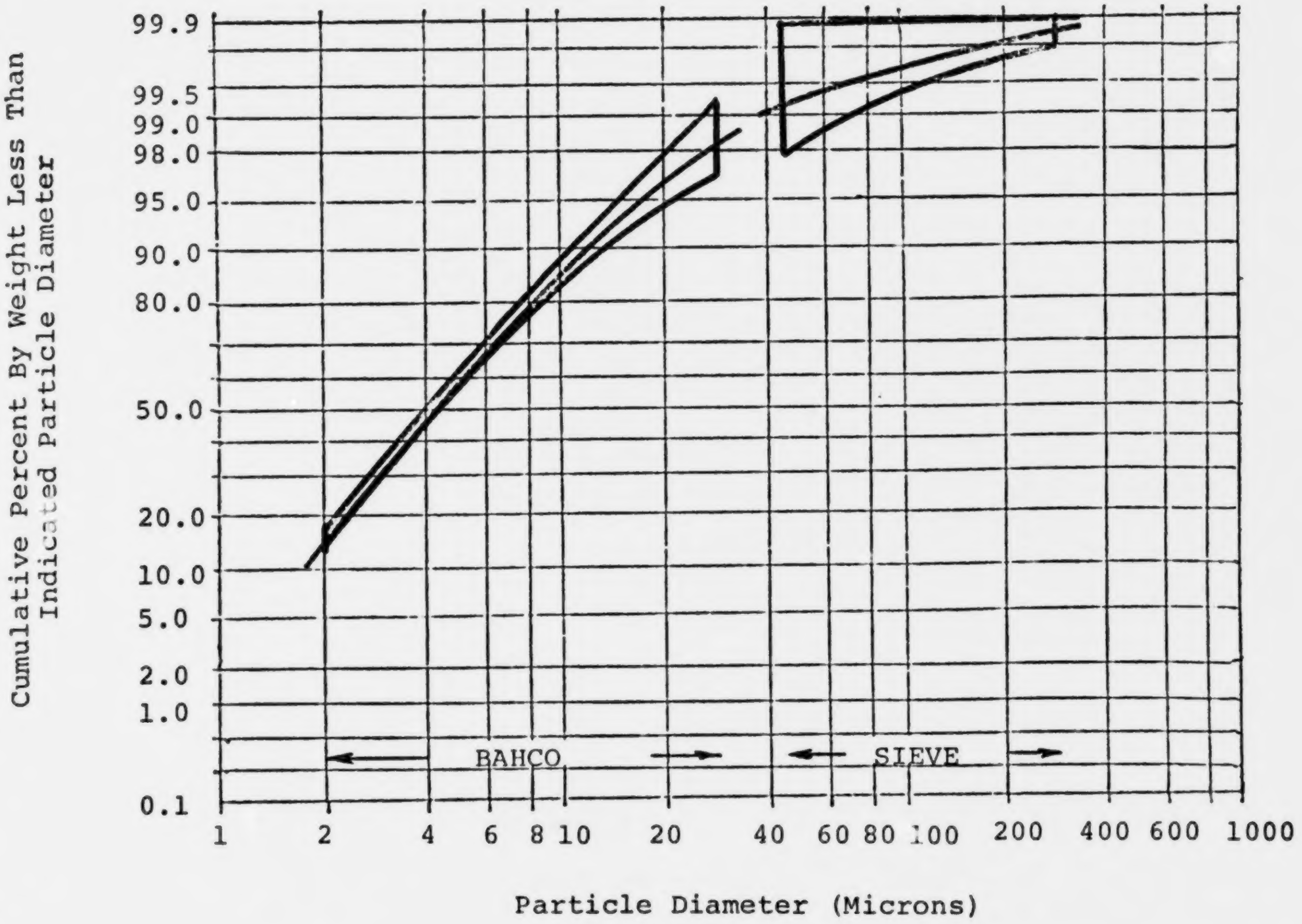


TABLE XXXI

FRACTIONAL EFFICIENCY OF DUST COLLECTORS - FLY ASH ONLY

(CES Test Series No. 1)

	MECHANICAL COLLECTOR FRACTION IN INTERVAL				ELECTROSTATIC PRECIPITATOR FRACTION IN INTERVAL				PERCENT FRACTIONAL EFFICIENCY(1)	
Micron Size Interval	Inlet	Outlet	Hopper	Hopper & Outlet	Inlet	Outlet	Hopper	Hopper & Outlet	Mechanical Collector	Electrostatic Precipitator
0-2	6.5	4.7	2.0	6.7	11.0	2.7	13.8	16.5	29.9	83.6
2-4	9.5	10.7	2.0	12.7	25.0	3.5	25.0	28.5	15.8	87.8
4-6	7.0	8.1	2.6	10.7	19.0	2.2	15.5	17.7	24.4	87.7
6-8	7.0	5.5	2.3	7.8	13.0	1.4	10.4	11.8	29.5	88.3
8-10	4.0	3.4	2.0	5.4	8.0	0.7	5.2	5.9	37.1	88.2
10-15	10.0	3.8	4.6	8.4	9.0	1.1	7.8	8.9	54.7	87.6
15-20	8.0	3.4	6.3	9.7	8.0	0.9	4.3	5.2	65.0	82.7
20-25	3.0	1.1	4.0	5.1	2.0	0.1	0.9	1.0	78.4	90.0
25-30	5.0	0.4	4.0	4.4	1.5	0.3	0.9	1.2	91.0	75.0
>30	40.0	1.5	27.6	29.1	3.5	0.7	2.6	3.3	92.3	78.8
	100.0	42.6	57.4	100.0	100.0	13.6	86.4	100.0		

(1) $\frac{\text{Hopper (100)}}{\text{Hopper + Outlet}}$

TABLE XXXII

FRACTIONAL EFFICIENCY OF DUST COLLECTORS - FINE LIMESTONE

	MECHANICAL COLLECTOR FRACTION IN INTERVAL				ELECTROSTATIC PRECIPITATOR FRACTION IN INTERVAL				PERCENT FRACTIONAL EFFICIENCY (1)	
Micron Size Interval	Inlet	Outlet	Hopper	Hopper & Outlet	Inlet	Outlet	Hopper	Hopper & Outlet	Mechanical Collector	Electrostatic Precipitator
0-2	6.5	4.3	1.7	6.0	10.0	2.9	11.1	16.5	28.4	79.3
2-4	13.5	8.4	3.1	11.5	23.0	8.6	19.2	27.8	27.0	69.1
4-6	12.0	8.0	3.7	11.7	18.0	6.9	13.2	20.1	31.6	65.7
6-8	11.0	6.7	2.8	9.5	15.0	4.6	6.2	10.8	29.5	57.4
8-10	9.0	3.6	2.3	5.9	8.0	3.1	3.1	6.2	39.0	50.0
10-15	13.0	5.8	6.2	12.0	11.0	3.8	4.9	8.7	51.7	56.3
15-20	12.0	4.0	5.7	9.7	9.0	1.9	2.2	4.1	58.8	53.6
20-25	3.0	0.9	1.1	1.9	2.0	1.3	0.3	1.6	58.0	18.8
25-30	4.0	0.9	5.0	5.9	2.0	1.4	0.5	1.9	84.9	26.3
>30	16.0	0.9	25.0	25.9	2.0	3.7	1.1	4.8	96.5	23.0
	100.0	43.4	56.6	100.0	100.0	38.2	61.8	100.0		

(1) $\frac{\text{Hopper (100)}}{\text{Hopper + Outlet}}$

TABLE XXXIII

FRACTIONAL EFFICIENCY OF DUST COLLECTORS - COARSE LIMESTONE

(CES Test Series No. 2)

	MECHANICAL COLLECTOR FRACTION IN INTERVAL				ELECTROSTATIC PRECIPITATOR FRACTION IN INTERVAL				PERCENT FRACTIONAL EFFICIENCY [1]	
Micron Size Interval	Inlet	Outlet	Hopper	Hopper & Outlet	Inlet	Outlet	Hopper	Hopper & Outlet	Mechanical Collector	Electrostatic Precipitator
0-2	11.0	3.4	1.8	5.2	7.0	0.6	14.2	14.8	34.6	95.9
2-4	17.0	11.0	2.8	13.8	23.0	2.4	28.4	30.8	20.3	92.3
4-6	11.0	10.3	3.6	13.9	21.0	1.9	19.6	21.5	25.9	91.3
6-8	9.0	6.8	2.1	8.9	14.0	1.6	9.8	11.4	23.6	86.1
8-10	6.0	4.4	2.1	6.5	9.0	1.0	4.6	5.6	32.2	82.2
10-15	11.0	5.3	4.1	9.4	11.0	1.4	8.0	9.4	43.5	88.8
15-20	7.0	3.4	4.1	7.5	7.0	1.0	2.7	3.7	54.7	73.0
20-25	3.0	0.5	1.5	2.0	1.0	0.1	0.3	0.4	75.0	75.0
25-30	5.0	1.5	3.1	4.6	3.0	0.4	1.1	1.5	67.5	73.3
>30	20.0	1.9	26.2	28.1	4.0	0.5	0.4	0.9	93.3	44.4
	100.0	48.5	51.5	100.0	10.9	89.1	100.0			

(1) $\frac{\text{Hopper (100)}}{\text{Hopper + Outlet}}$

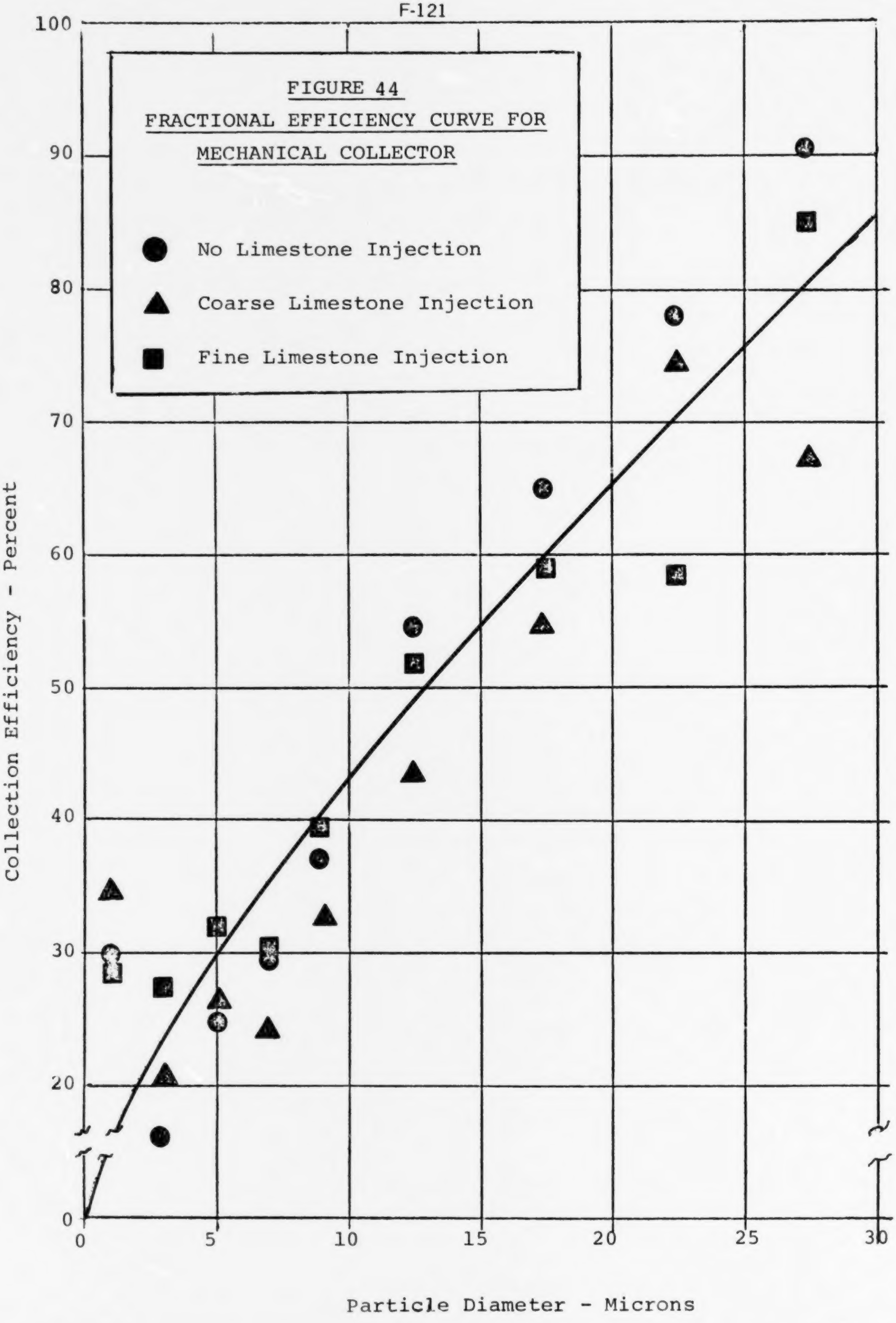


FIGURE 44
FRACTIONAL EFFICIENCY CURVE FOR MECHANICAL COLLECTOR

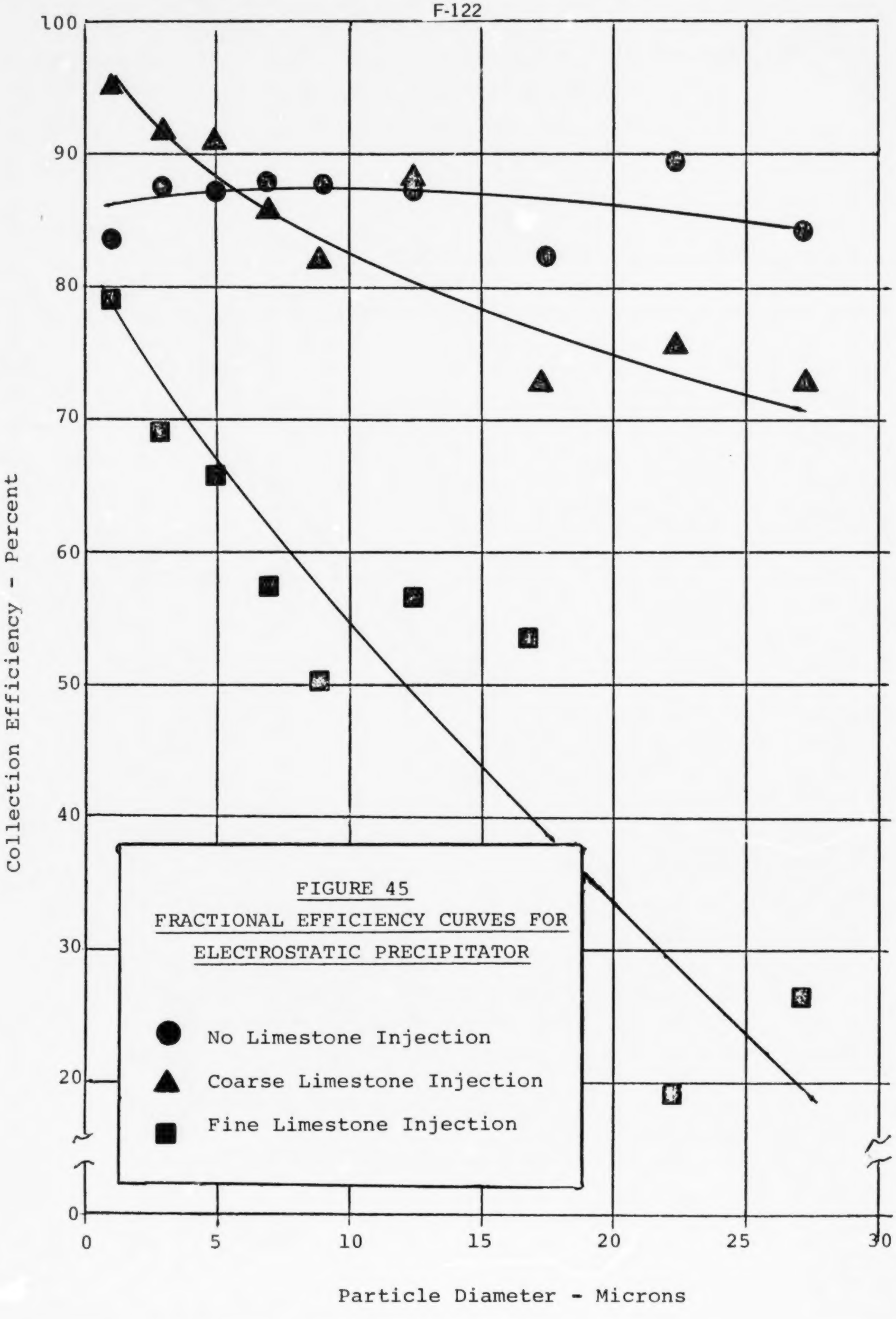


FIGURE 45
FRACTIONAL EFFICIENCY CURVES FOR
ELECTROSTATIC PRECIPITATOR

by weight of about 19 microns with a range of 12 to 30 microns for individual tests. The particulate from both the coarse and fine limestone injection tests had an average mean size of 8.5 to 9.5 microns regardless of injection rate. The individual tests ranged between 6 to 13 microns. As stated before, the raw limestone mean particle size ranged from 6 microns for fine to 17 microns for coarse.

The most plausible explanation for the particle size results obtained at the mechanical collector inlet with limestone injection is that the boiler, air heater, ductwork, etc. ahead of the mechanical collector are acting as a primary mechanical collector, particularly on the very fine and very coarse material. The fine limestone can plate out on surfaces by mechanical and thermal diffusion or electrostatic mechanisms while the coarse material is collected in low velocity ductwork areas and hoppers below the air heater by gravity, and impaction mechanisms. The overall effect of these collection mechanisms would be to make the particle size distribution at the mechanical collector inlet more uniform, and less dependent on the size distribution and amount of injected limestone. Other possibilities include agglomeration or attachment of fines to larger particles (fly ash) by impaction, ineffective dispersion of fines during injection, better calcination on the coarse material resulting in decreased size by carbon dioxide loss, and higher utilization of fines in reacting with sulfur oxides causing an increase in particle size of the reaction products.

The average particle loading at the mechanical outlet-precipitator inlet varies with limestone injection rate (see Figure 46) from about 1.5 grains/SCF with no limestone addition to about 4.0 grains/SCF with 16 tons/hour limestone feed into the boiler.

3. Discussion of Particle Resistivity Data

A. Correlation of In-Situ and Laboratory Resistivity Measurements

As discussed in an earlier section of the report, a fundamental parameter in electrostatic precipitation is the electrical resistivity of the particulate. Many industrial dusts are poor conductors and as a result inhibit the performance of precipitators. Generally, the critical value above which precipitation is deleteriously affected is somewhere between 10^{10} and 10^{11} ohm-cm.[6] The gas temperature and moisture content are the two main factors having the strongest influence on resistivity. Secondary agents present in some industrial gases, e.g. sulfur trioxide, can drastically change resistivity. It is this particular agent which appears to cause the differences in laboratory and in-situ resistivity of fly ash from coal fired boilers. (Sulfur trioxide cannot be simulated conveniently in the laboratory test gas.) Furthermore, the addition of large amounts of alkali material such as ground limestone to the boiler flue gas which removes the sulfur trioxide by chemical reaction is believed to result in degraded precipitation rates. An objective of the test program was to measure the effects of limestone injection on resistivity and precipitation rates.

TABLE XXXIV

SUMMARY OF PARTICLE SIZE ANALYSES ON SAMPLES FROM BOTH CES TEST SERIES

(From Figures 26 to 43)

Sample Point	Description	Test Numbers	Average Geometric Mean Size (μ)	Specific Gravity	Range of Geometric Mean Size For Individual Tests (μ)
Limestone Feeder	Coarse	14, 32, 33	17	2.55	15 - 20
Limestone Feeder	Fine	6, 8, 23, 24	6.0	2.54	5 - 7
MC Inlet	Fly Ash Only	1A&B, 3A, 4A&B, 5A&B	19	2.36	12 - 30
ESP Inlet	Fly Ash Only	1A&B, 3A, 4A&B, 5A&B	5.5	2.31	5 - 6.5
ESP Outlet	Fly Ash Only	2A, 3A&B, 4B	4.5	1.98	3.5 - 5.5
MC Hopper	Fly Ash Only	1A&B, 2A, 3A&B, 4A&B, 5A&B	28	2.32	24 - 33
ESP Hopper	Fly Ash Only	1A&B, 2A, 3A, 4A, 5A&B	4.6	2.04	4.2 - 5.2
ESP Inlet	Fly Ash Only	16, 19, 20, 21, 22	7.0	2.53	4.5 - 9
ESP Hopper	Fly Ash Only	16, 21, 22	4.0	2.30	3.8 - 4.3
MC Inlet	Fly Ash & Coarse Limestone Reaction Products	14, 15, 32, 33	8.5	2.69	6.2 - 13
ESP Inlet	Fly Ash & Coarse Limestone Reaction Products	10, 11, 14, 15, 25, 32, 33	6.0	2.67	5 - 7

TABLE XXXIV (Continued)

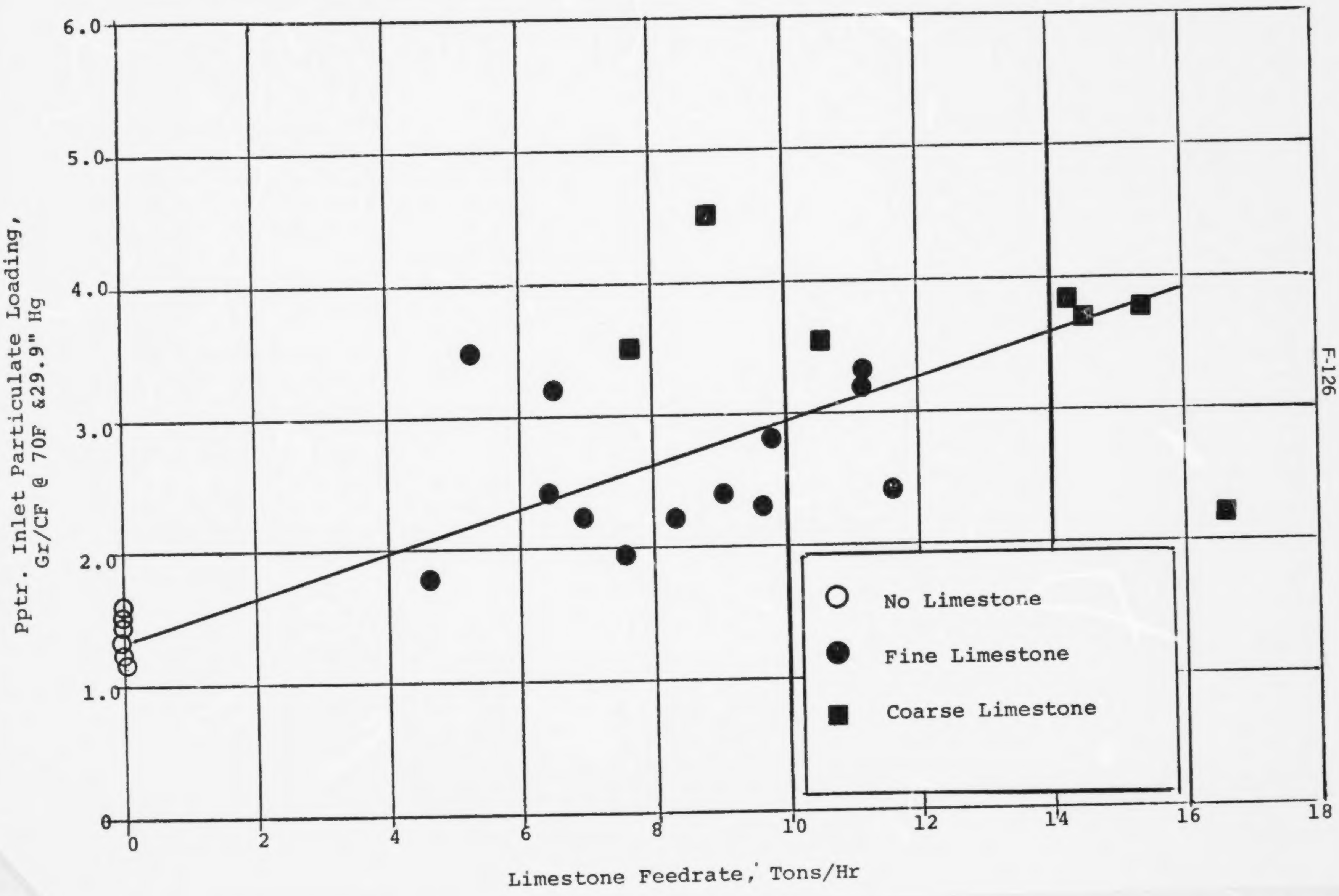
SUMMARY OF PARTICLE SIZE ANALYSES
ON SAMPLES FROM BOTH CES TEST SERIES

(From Figures 26 to 43)

Sample Point	Description	Test Numbers	Average Geometric Mean Size (μ)	Specific Gravity	Range of Geometric Mean Size For Individual Tests (μ)
ESP Outlet	Fly Ash & Coarse Limestone Reaction Products	11, 14	6.6	3.05	5.8 - 8
MC Hopper	Fly Ash & Coarse Limestone Reaction Products	14, 15, 32, 33	30	2.85	26 - 40
ESP Hopper	Fly Ash & Coarse Limestone Reaction Products	14, 15	4.2	2.53	3.8 - 4.7
MC Inlet	Fly Ash & Fine Limestone Reaction Products	2, 3, 5, 6, 8	9.5	3.08	8 - 13
ESP Inlet	Fly Ash & Fine Limestone Reaction Products	2,3,4,5,6,8, 17,18,23,24, 26,27,28,29,30	5.8	2.78	4.5 - 8.5
ESP Outlet	Fly Ash & Fine Limestone Reaction Products	2, 3, 4, 5, 6, 23, 24, 26	6.5	2.09	4.5 - 11
MC Hopper	Fly Ash & Fine Limestone Reaction Products	2, 3, 5, 6, 8	23	2.71	20 - 27
ESP Hopper	Fly Ash & Fine Limestone Reaction Products	17, 18, 23, 24	4.1	2.63	3.9 - 4.3

FIGURE 46

ELECTROSTATIC PRECIPITATOR PARTICULATE INLET LOADING AS A FUNCTION OF LIMESTONE FEEDRATE



In Figure 47, the in-situ resistivities obtained for coal firing only on full-scale boilers at Shawnee Station of TVA and a large midwest utility, and on a pilot scale combustor at Babcock and Wilcox Company Research Center are plotted as a function of gas temperature. Figure 48 displays in-situ resistivities obtained during limestone injection tests by the same organizations. The Shawnee data was obtained by Southern Research Institute[2] (see Table XXXV), K. J. McLean[5] (see Figure 49), and Cottrell Environmental Systems (see Tables XXIII through XXV). The midwest utility data was obtained by Research-Cottrell, Inc.[3] (see Table XXXVI). The pilot scale Babcock and Wilcox data[4] for coal firing is reproduced in Figure 50 and shown for comparison with full-scale data as a dotted line polygon in Figure 47. Similarly, the Babcock and Wilcox limestone injection data is reproduced in Figures 51 through 53 and shown as a dotted line polygon in Figure 48.

Laboratory resistivity measurements obtained on precipitator inlet samples taken during the Cottrell Environmental Systems test series are shown in Figures 54 (without limestone injection) and 55 (with limestone injection). The in-situ measurements from Figures 47 and 48 are superimposed on this data as solid lined polygons. Note that although the data is scattered, due to variations in ash composition, coal sulfur, etc., there is a general indication that laboratory measurements are higher than in-situ at a given gas temperature. Of further interest is that at temperatures in the 550 to 650° F range, the resistivities (lab and in-situ) are coming closer to coinciding, while at temperatures below 500° F agreement is poor. This is further evidence that the flue gas and laboratory test gas are not equivalent, and trace constituents in the flue gas are affecting resistivity due to surface conductivity (most prevalent at low gas temperatures), but are not critical at the high temperatures where the bulk resistivity of the constituents of the ash is controlling.

B. Relationship of Particle Resistivity, Flue Gas Temperature, and Coal Sulfur (No Limestone Injection)

In general, the higher the percentage sulfur in the coal, the more sulfur trioxide appearing in the flue gas. Typically, 1 to 2% of the coal sulfur is converted to the trioxide. This amounts to about 3 to 6 parts per million by volume in the flue gas for 0.5% sulfur coal and six times this amount for 3% sulfur coal. Normally, 15 to 25 parts per million at 300° F is sufficient to condition the dust surface by sulfuric acid condensation giving resistivities in the 10^{10} ohm-cm range or lower. At lower temperatures, less amounts of sulfur trioxide are required and gas moisture content becomes more important. Conversely, at high temperatures, the bulk resistance of the material is controlling, and the coal sulfur and moisture are not critical. Figure 56 is a plot of particle resistivity as a function of flue gas temperature for a range of coal sulfur. The data were taken from Tables XXIII through XXV, and Table XXV.

FIGURE 47

IN-SITU RESISTIVITIES OBTAINED ON FULL-SCALE & PILOT SCALE PULVERIZED COAL-FIRING BOILERS WITHOUT LIMESTONE INJECTION

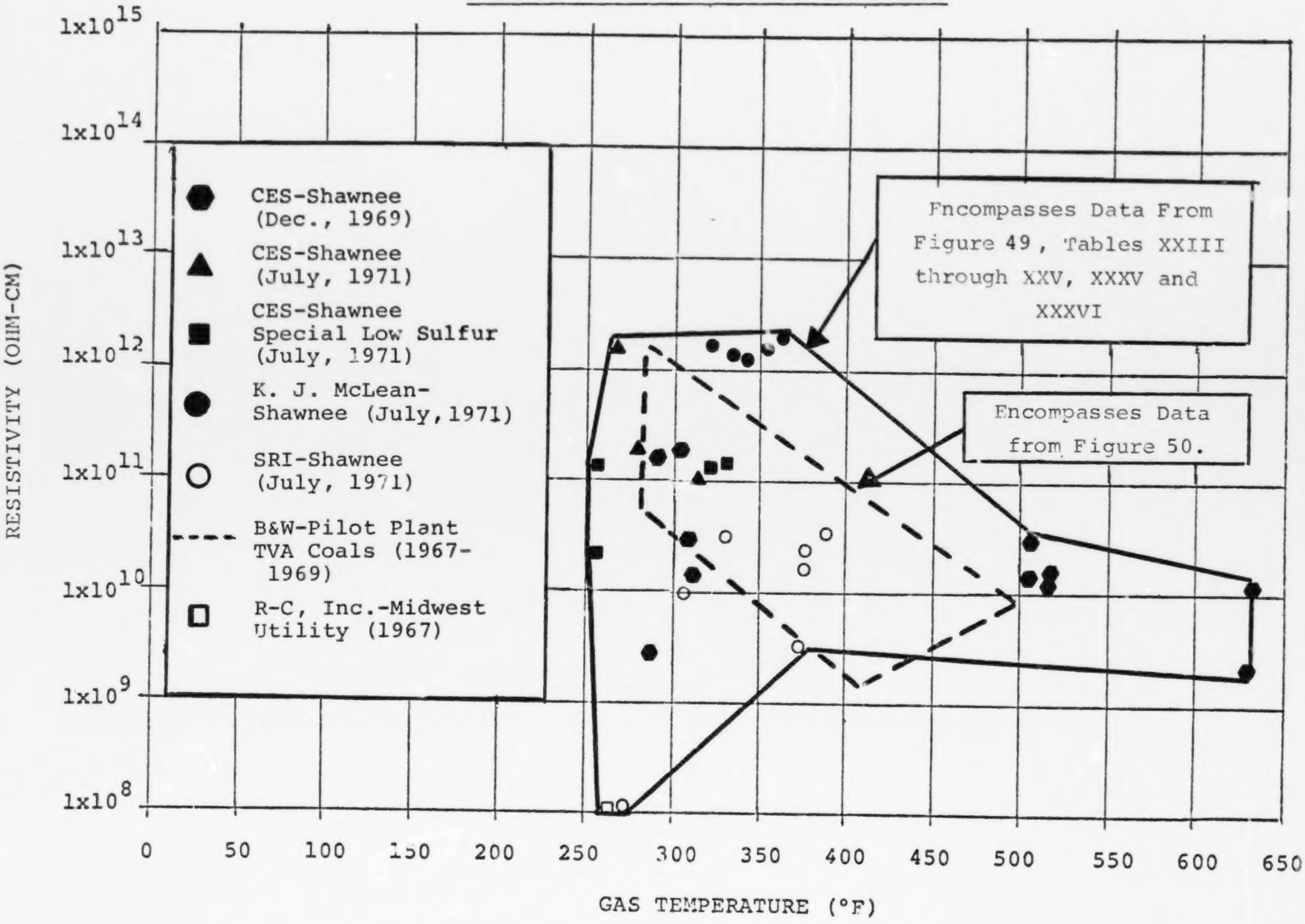


FIGURE 48

IN-SITU RESISTIVITIES OBTAINED ON FULL SCALE AND PILOT SCALE PULVERIZED COAL FIRING BOILERS WITH LIMESTONE INJECTION

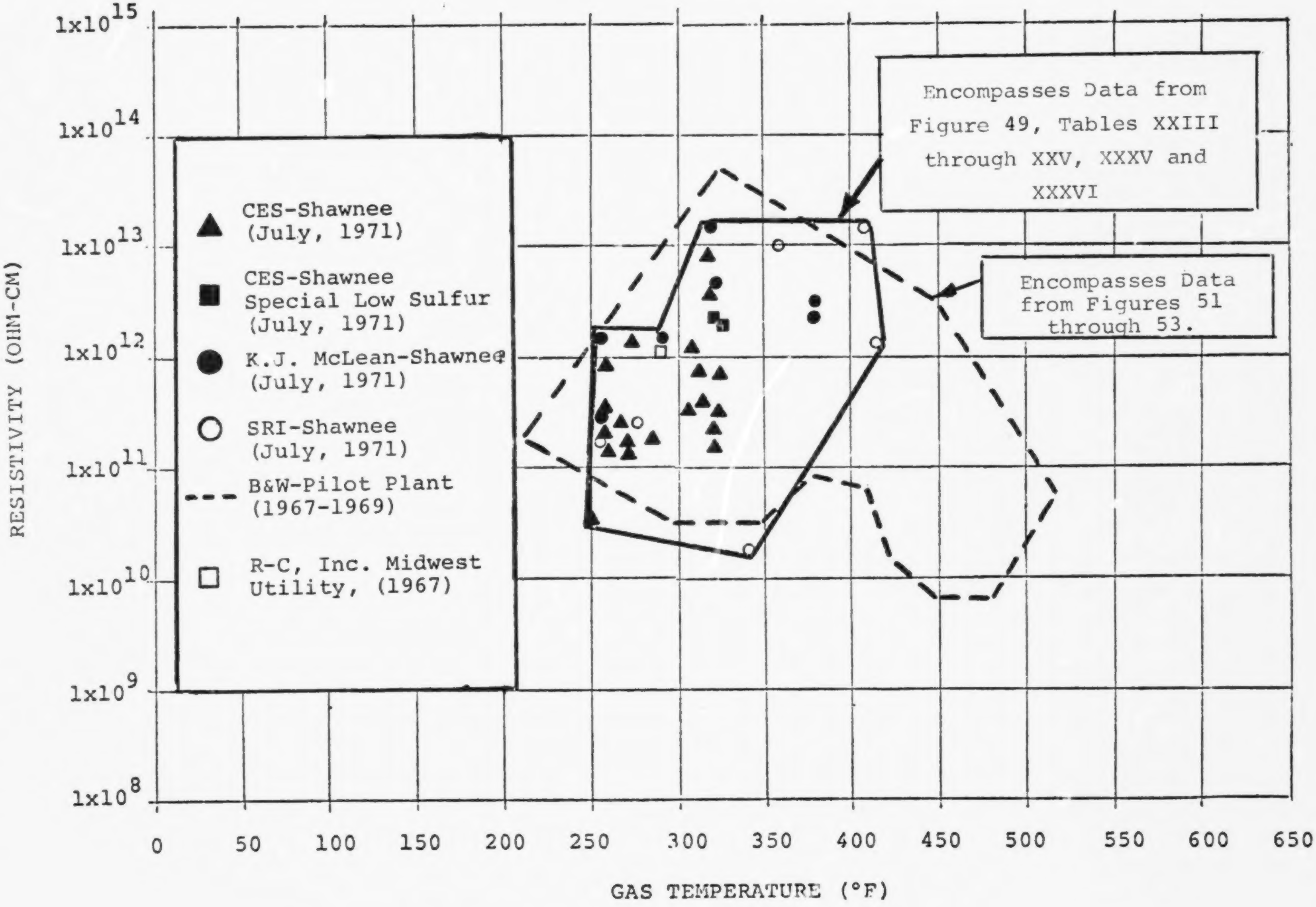


TABLE XXXV

IN-SITU RESISTIVITY DATA OBTAINED BY SOUTHERN RESEARCH INSTITUTE AT TVA SHAWNEE STATION, BOILER #10 DURING THE CES SECOND TEST SERIES

Date	Reported Injection Rate of $CaCO_3$, Lb./Min.	Temp., ^{o}F	Resistivity, ohm cm, at various electric fields					
			1.0 KV/cm	2.5 KV/cm	5.0 KV/cm	10.0 KV/cm	15.0 KV/cm	20.0 KV/cm
July 15	333	340	---	---	3.0 x 10^{10}	2.7 x 10^{10}	---	---
July 16	333	255	---	---	4.0 x 10^{11}	2.4 x 10^{11}	1.5 x 10^{11}	9.0 x 10^{10}
	333	273	---	---	4.5 x 10^{11}	4.5 x 10^{11}	4.5 x 10^{11}	4.5 x 10^{11}
July 21	167	407	---	---	1.3 x 10^{13}	1.7 x 10^{13}	2.3 x 10^{13}	2.6 x 10^{13}
	333	360	---	---	1.1 x 10^{13}	1.0 x 10^{13}	9.0 x 10^{12}	8.0 x 10^{12}
July 22	333	417	4.0 x 10^{11}	5.0 x 10^{11}	8.0 x 10^{11}	1.2 x 10^{12}	1.6 x 10^{12}	2.0 x 10^{12}

(a) With Limestone Injection

Date	Temp., ^{o}F	Resistivity, ohm cm, at various electric fields					
		1.0 KV/cm	2.5 KV/cm	5.0 KV/cm	10.0 KV/cm	15.0 KV/cm	20.0 KV/cm
July 15	375	2.3 x 10^{10}	1.4 x 10^{10}	8.0 x 10^{9}	5.0 x 10^{9}	---	---
	376	---	---	3.5 x 10^{10}	2.0 x 10^{10}	1.8 x 10^{10}	1.8 x 10^{10}
July 16	266	---	8.0 x 10^{10}	3.5 x 10^{10}	1.2 x 10^{8}	6.0 x 10^{7}	5.0 x 10^{7}
	273	---	---	2.3 x 10^{10}	8.0 1 10^{7}	---	---
	305	7.0 x 10^{10}	4.0 x 10^{10}	1.8 x 10^{10}	1.0 x 10^{10}	---	---
July 21	330	5.5 x 10^{10}	5.0 x 10^{10}	5.0 x 10^{10}	4.2 x 10^{10}	3.6 x 10^{10}	---
July 22	375	5.8 x 10^{10}	5.0 x 10^{10}	4.0 x 10^{10}	3.0 x 10^{10}	2.5 x 10^{10}	---
	385	8.0 x 10^{10}	7.0 x 10^{10}	6.0 x 10^{10}	4.6 x 10^{10}	3.8 x 10^{10}	3.0 x 10^{10}

(b) Without Limestone Injection

FIGURE 49

IN-SITU RESISTIVITY DATA OBTAINED BY K.J. McLEAN AT TVA SHAWNEE STATION, BOILER #10 DURING THE CES SECOND TEST SERIES

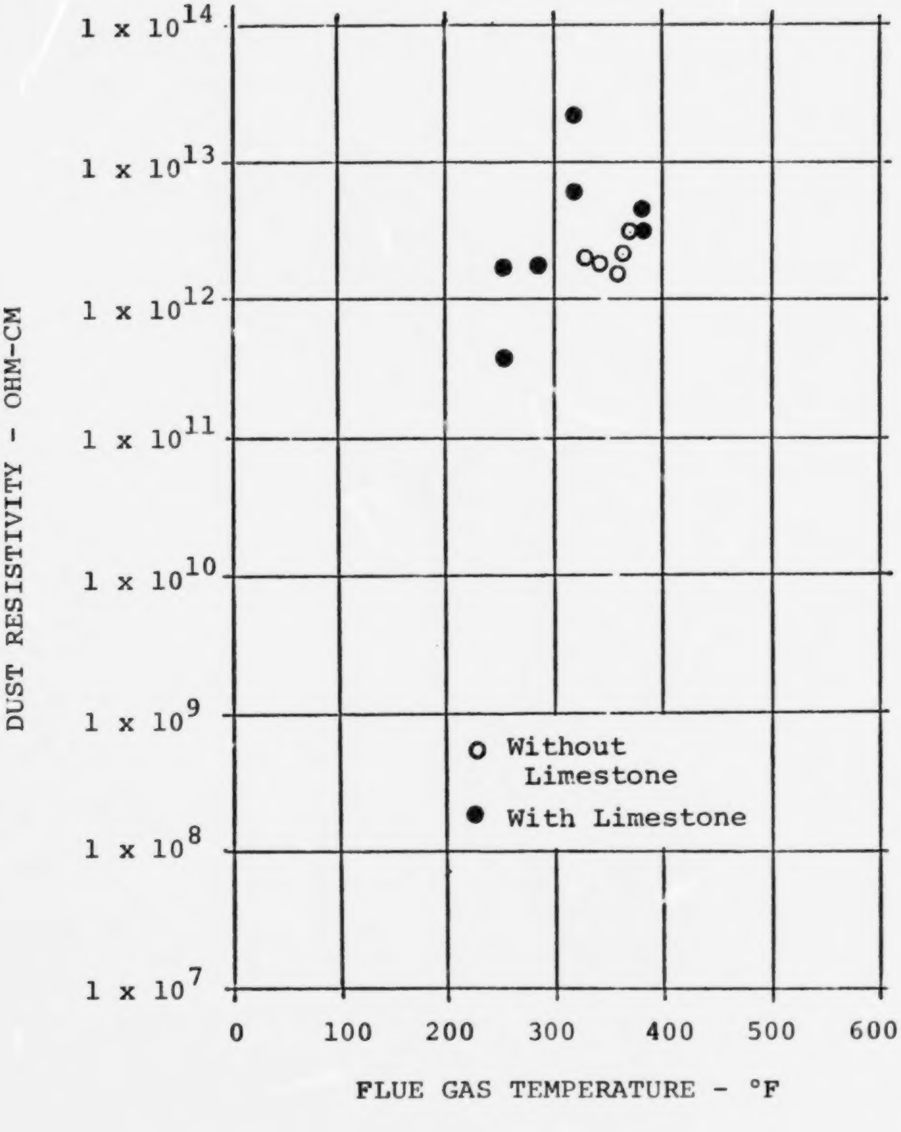


TABLE XXXVI

DATA SUMMARY - FULL SCALE DOLOMITE INJECTION TEST RESULTS OBTAINED BY RESEARCH-COTTRELL, INC. AT A LARGE MIDWEST UTILITY

Parameter	Boiler	
	Reheat	Superheat
Dolomite Injected-Tph	6	0
Coal Fired - Tph	60	65-70
Gas Vol. @ Pptr, ACFM	492,000	568,000
Gas Temp. @ Pptr. °F	287	270
SO_2 PPM by Volume	1,950	2,550
SO_3 PPM by Volume	Nil	17
Dust Concentrations (gr/SCFD)		
Mechanical Inlet	6.10	3.70
Precipitator Inlet	1.32	0.74
Precipitator Outlet	0.60	0.16
Efficiencies %		
Mechanical	78.3	80.0
Precipitator	55.0	78.8
Overall	90.2	95.8
In-Situ Resistivity - ohm-cm	1×10^{12}	1×10^{8}
Precipitation Rate - FPS	0.15	0.34

FIGURE 50

RESISTIVITY OF FLY ASH SAMPLES FROM VARIOUS COALS FIRED IN PILOT PLANT OF B&W

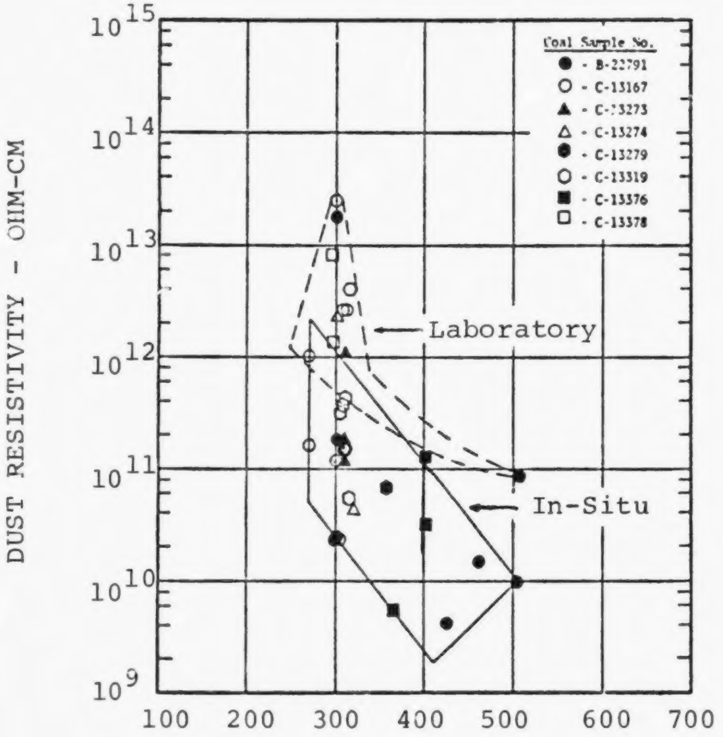
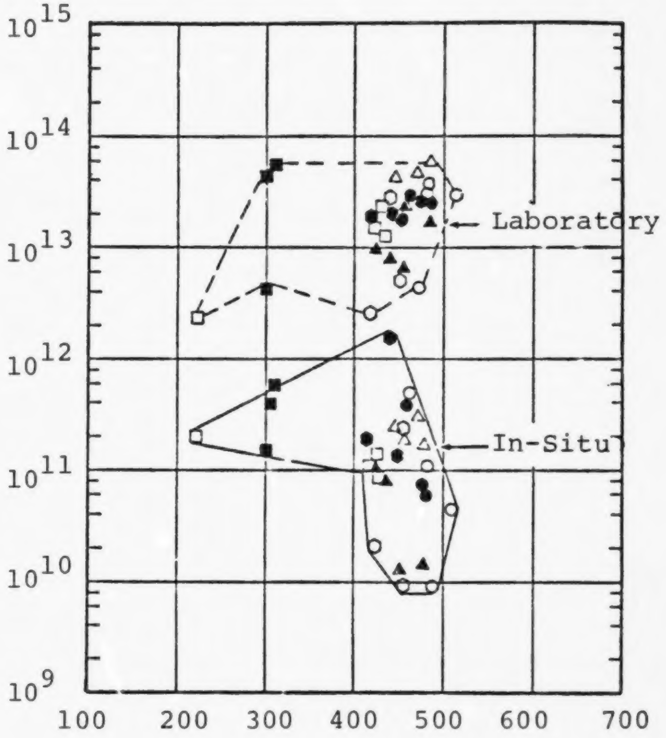


FIGURE 51

IN-SITU AND LABORATORY RESISTIVITIES FOR REACTED ADDITIVE-FLY ASH SAMPLES FROM B&W PILOT PLANT



FLUE GAS TEMPERATURE, °F

FIGURE 52

IN-SITU AND LABORATORY RESISTIVITIES FOR REACTED ADDITIVE-FLY ASH MIXTURES FROM B&W PILOT PLANT

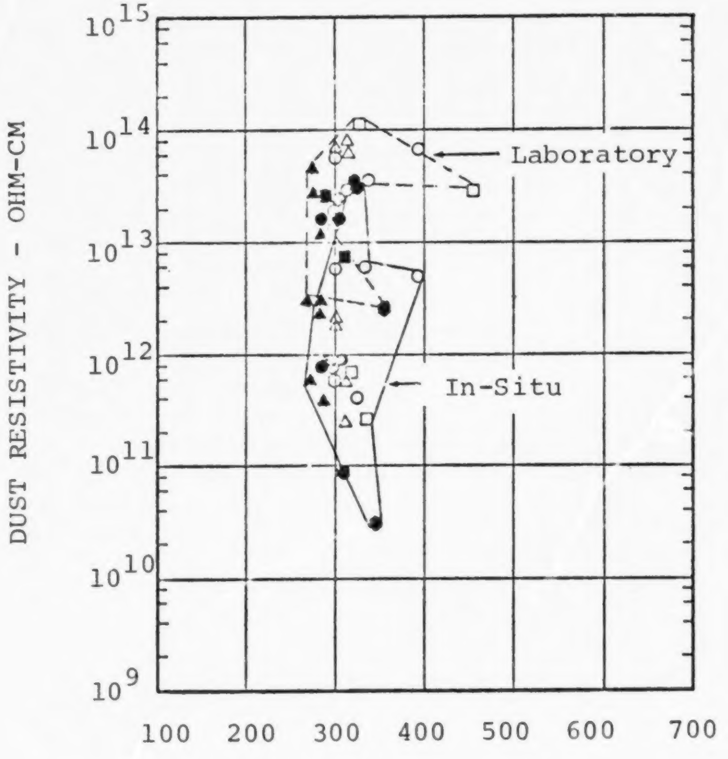


FIGURE 53

IN-SITU AND LABORATORY RESISTIVITIES FOR REACTED ADDITIVE-FLY ASH MIXTURES FROM B&W PILOT PLANT

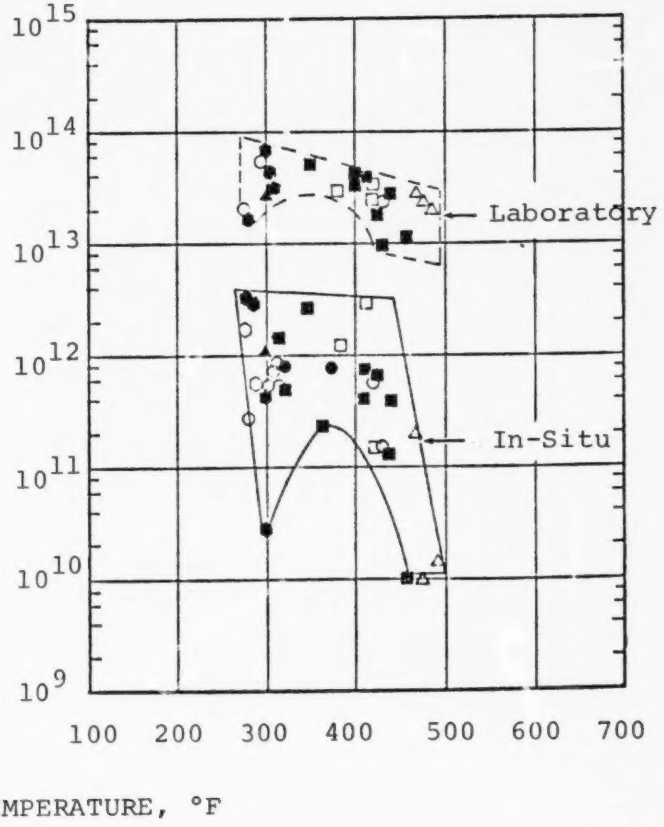


FIGURE 54

LABORATORY RESISTIVITY MEASUREMENTS ON PRECIPITATOR INLET SAMPLES AS A FUNCTION OF GAS TEMPERATURE WITHOUT LIMESTONE INJECTION

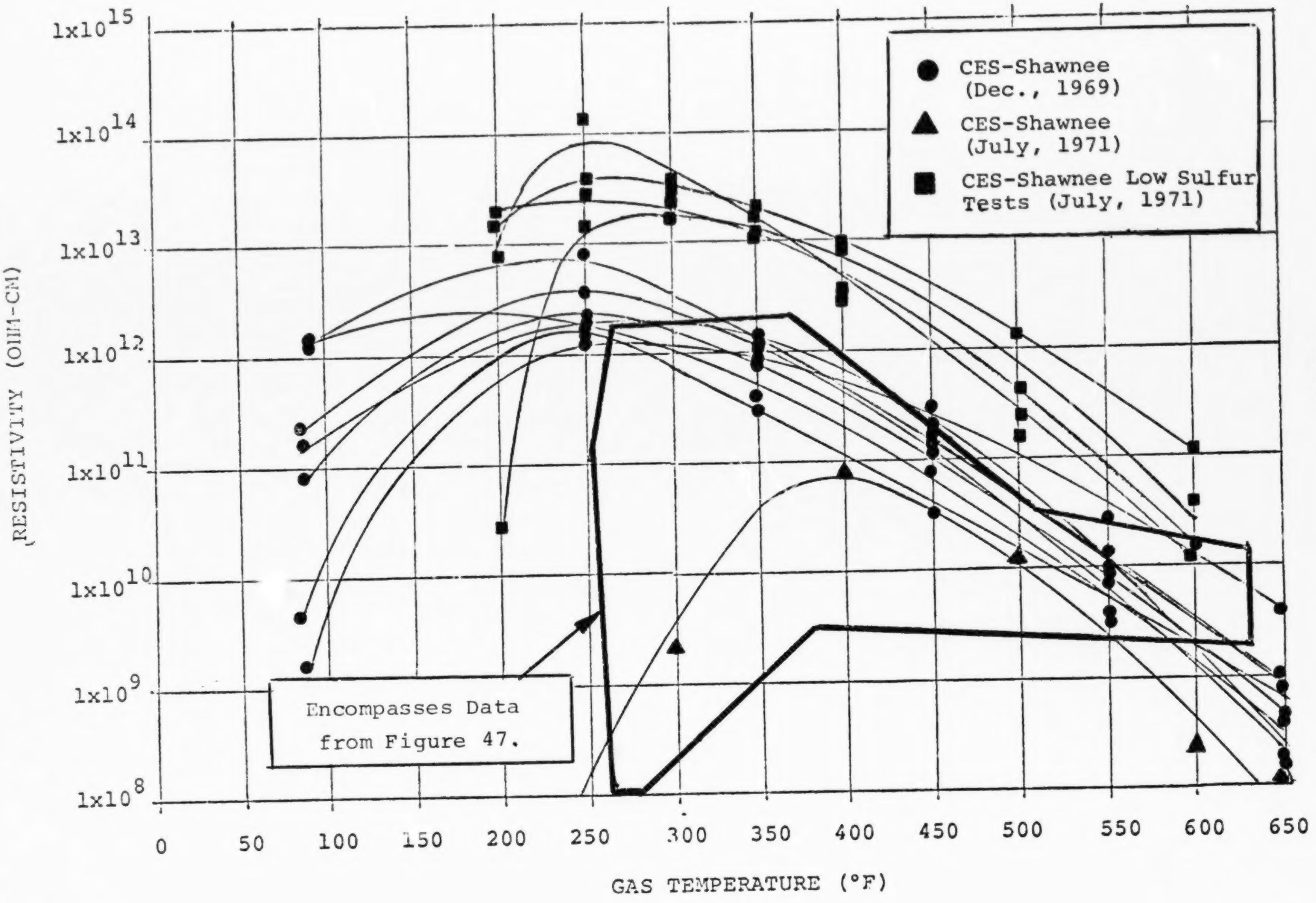
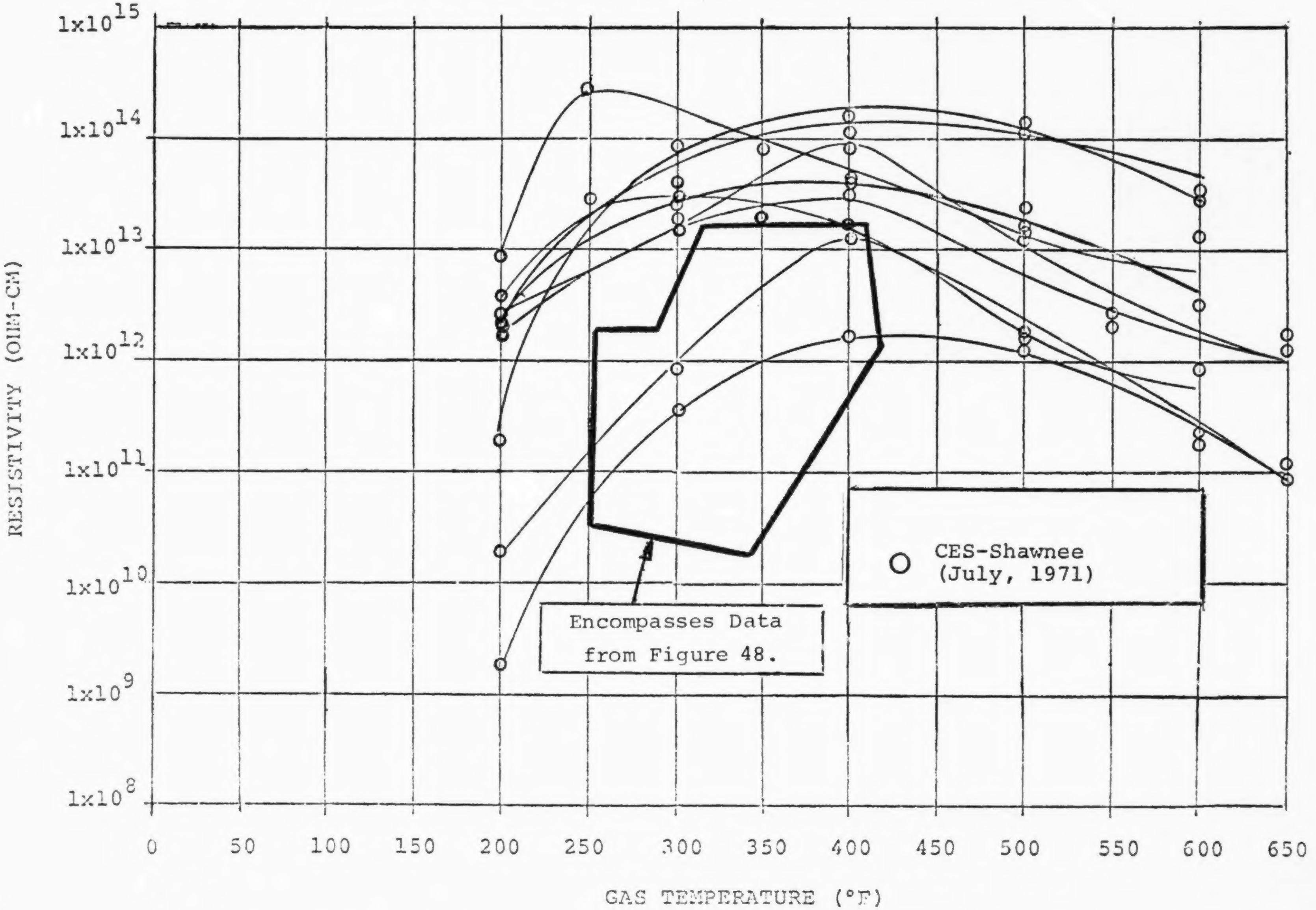


FIGURE 55

LABORATORY RESISTIVITY MEASUREMENTS ON PRECIPITATOR INLET SAMPLES AS A FUNCTION OF GAS TEMPERATURE WITH LIMESTONE INJECTION



The midwest utilities data are from unpublished Research-Cottrell, Inc., reports.[12,13] The criticality of coal sulfur and moisture on particle resistivity are graphically demonstrated in the lower temperature ranges (varies five orders of magnitude for 0.5 to 4.0% sulfur), while at the higher temperatures the effect is nearly independent of coal sulfur (varies about one order of magnitude).

C. Relationship of Particle Resistivity, Flue Gas Temperature, and Coal Sulfur (with Limestone Injection)

Normal expectation with a dry alkaline additive, such as limestone to the boiler or into flue gas, is a chemical reaction with the sulfur oxides formed, particularly the trioxide, resulting in a decreased conditioning effect and a higher particulate resistivity. Consequently, the sulfur content of the coal will become relatively independent in its affect on resistivity. In Figure 57, the particulate resistivity is plotted as a function of flue gas temperature with the coal sulfur indicated for each data point. The data were taken from tables and reports as noted above. Of particular interest is the observation that coal sulfur appears to affect the resistivity in a random manner. Nevertheless, the data still shows the affect of low temperature surface conditioning on resistivity. Apparently, this is due mainly to the moisture in the gas plus a few parts per million of sulfur trioxide not removed by the limestone. (See Table 4.14 in Reference 4, and Tables 41 and 44 in Reference 2.)

D. Relationship Between Precipitation Rate Parameter and Particle Resistivity

In establishing the precipitation rate parameter of a dust, the most critical single parameter is the electrical resistivity. Figure 58 graphically demonstrates the degradation of the precipitation rate parameter with resistivity. Two solid line-curves, taken from the literature[6,7] are shown. Data points (Table XXXVII) from the Shawnee tests, and a large midwest utility, are plotted for comparison purposes. Verification of the degradation noted above is indicated. However, the critical range of resistivity seems to be occurring between values of 10^{11} and 10^{13} ohm-cm. Obviously, more specific data are required to quantitatively establish the relationship between precipitation rate parameter and resistivity.

4. Discussion of Chemical Analyses Results

All the chemical analyses on particulate samples obtained during the test program were performed by TVA personnel at the Chattanooga, Tennessee, Laboratory (see Tables XXVII through XXIX). A summary of the data used in the following discussion and correlations are contained in Table XXXVIII.

FIGURE 56

IN-SITU RESISTIVITY VS. TEMPERATURE RELATIONSHIP FOR VARIOUS COAL SULFURS (No Limestone Injection)

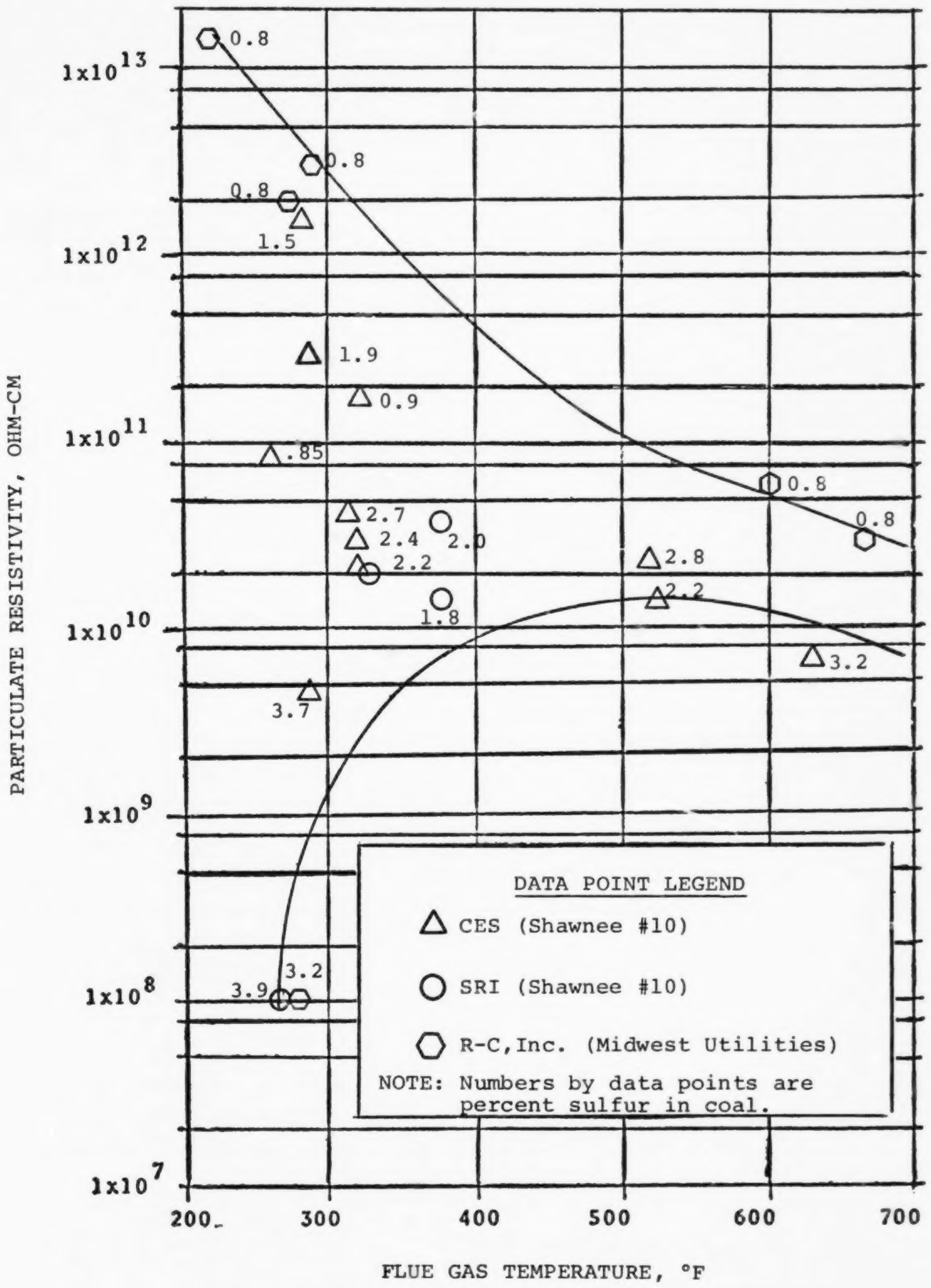


FIGURE 57

IN-SITU RESISTIVITY VS. TEMPERATURE RELATIONSHIP FOR VARIOUS COAL SULFURS

(With Limestone Injection)

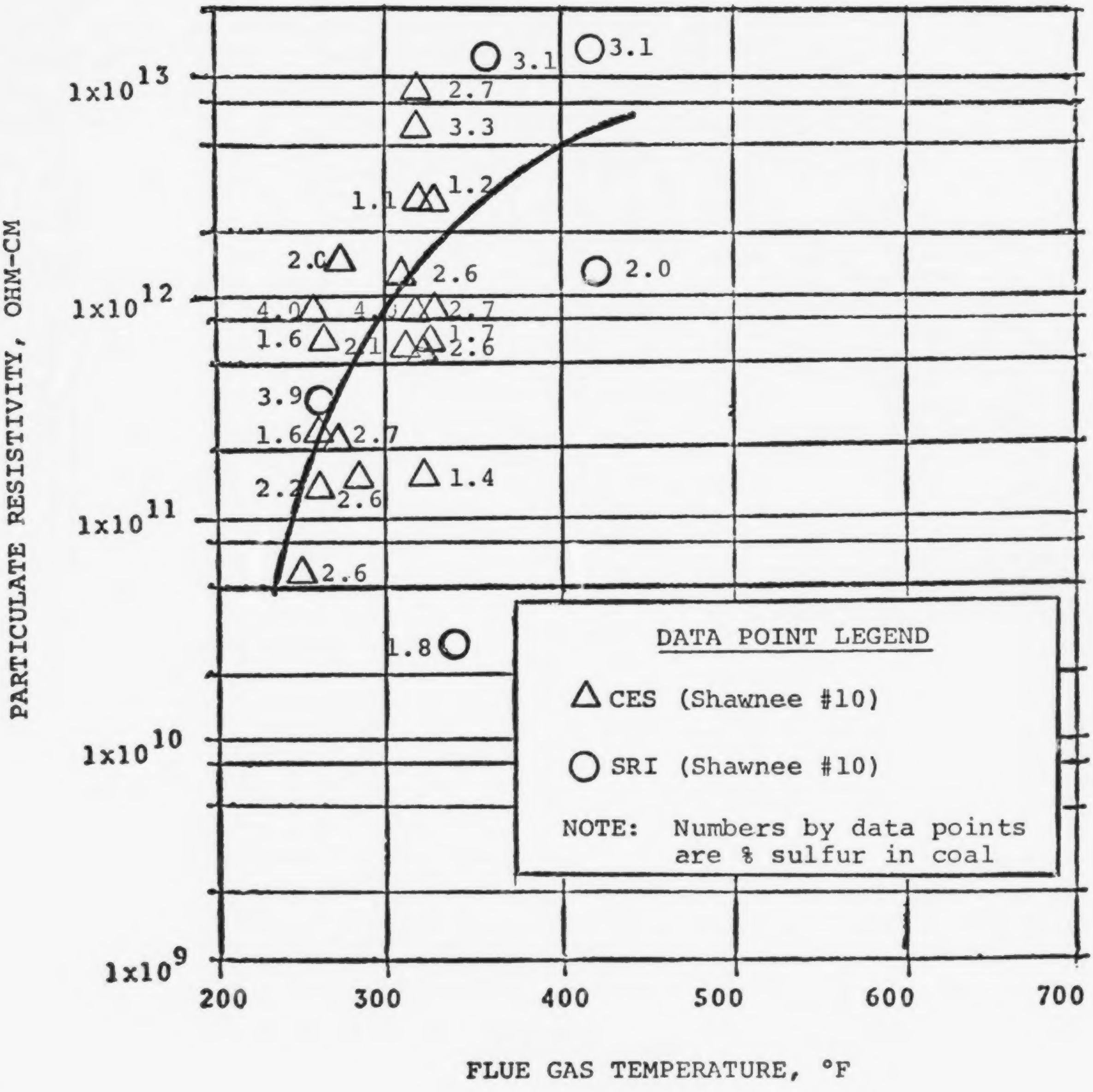


FIGURE 58

APPROXIMATE PRECIPITATION RATE PARAMETER VS. RESISTIVITY RELATIONSHIP WITHOUT AND WITH LIMESTONE INJECTION

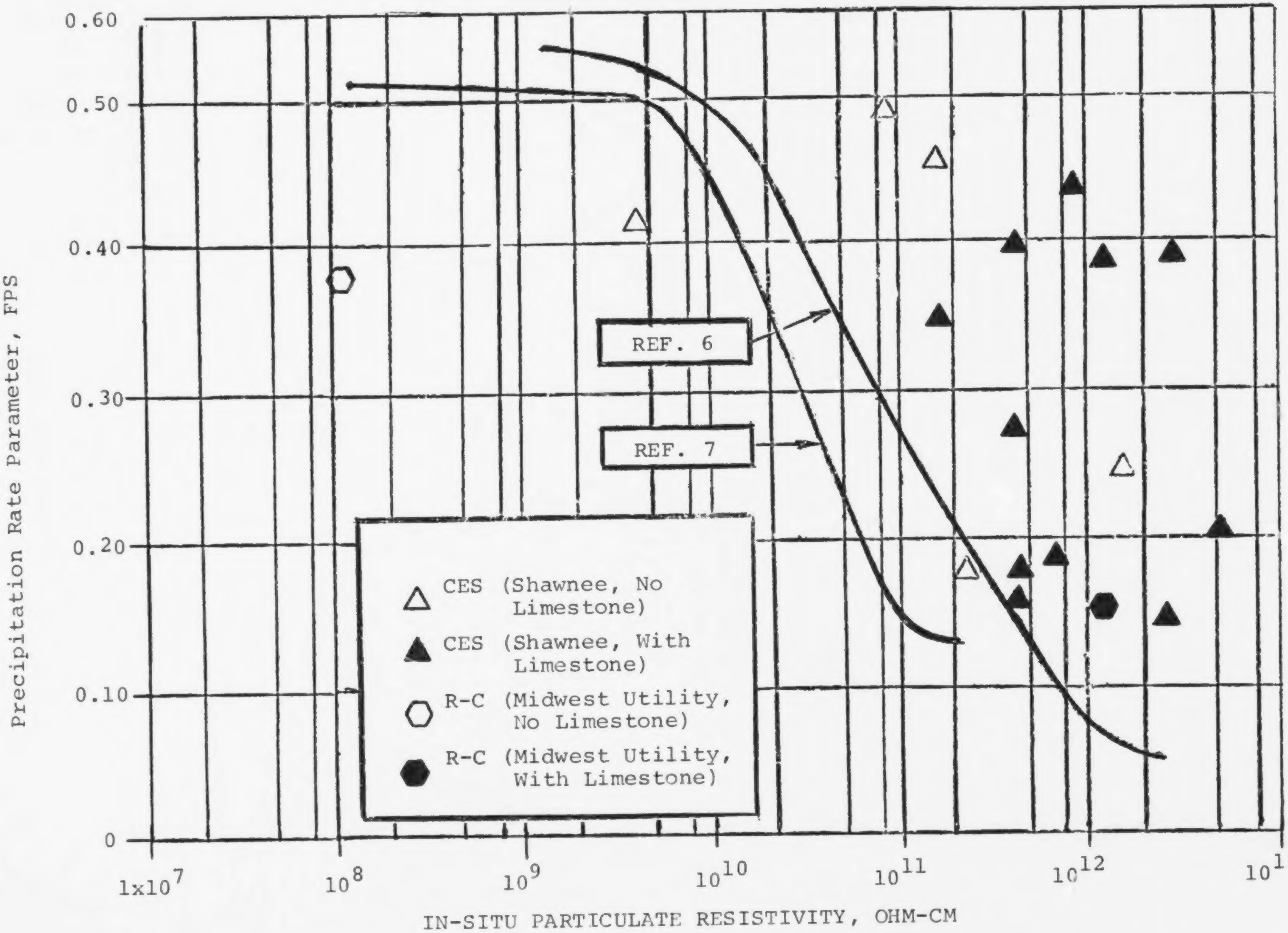


TABLE XXXVII

DATA USED FOR RELATIONSHIP BETWEEN PRECIPITATION RATE PARAMETER AND PARTICULATE RESISTIVITY

Source	Test No.	Flue Gas Temp. °F	Coal Sulfur %	In-Situ Resistivity ohm-cm	Pptn. Rate Parameter FPS	Comment
CES First Test Series Shawnee #10 December 1969	5A, 5B	300	3.22	4.8×10^{9}	0.42	No Limestone Injection
	3B, 4B	298	1.90	2.8×10^{11}	0.19	
	9, 16	275	1.54	1.6×10^{12}	0.26	
	19, 21	260	0.85	8.4×10^{10}	0.49	
	20, 22	326	0.90	1.8×10^{11}	0.47	
R-C, Inc. Midwest Utility	----	270	3.20	1.0×10^{8}	0.34	
CES Second Test Series Shawnee #10 July 1971	6, 14	322	2.66	7.3×10^{11}	0.18	With Limestone Injection
	10, 17	261	1.61	4.5×10^{11}	0.40	
	4, 11	323	1.53	4.1×10^{11}	0.16	
	8	285	2.59	1.9×10^{11}	0.35	
	2, 30	316	2.61	5.1×10^{12}	0.21	
	18, 26	318	2.20	4.0×10^{11}	0.17	
	23, 24	326	1.15	3.3×10^{12}	0.14	
	25, 27	271	1.87	1.3×10^{12}	0.38	
	28, 32	323	3.70	3.4×10^{12}	0.39	
	29	265	2.30	4.3×10^{11}	0.27	
	33	260	4.04	9.1×10^{11}	0.43	
R-C, Inc. Midwest Utility	----	287	3.20	1.2×10^{12}	0.15	

A. Relationship of Calcium Compounds at Electrostatic Precipitator Inlet with Limestone Feedrate

Since the dust collecting equipment is a combination mechanical-electrostatic unit, it is of interest to determine the effect on the dust chemical composition at the precipitator inlet caused by the mechanical collector for no, coarse, and fine limestone injection. One basis for doing this is to correlate the total amount of calcium reported as calcium oxide, as a function of the amount and particle size of the limestone fed into the boiler. Using the measured inlet grain loadings and gas volumes at the precipitator inlet, a rate in tons/hour of calcium oxide was calculated from the sample analyses. These were then plotted as a function of limestone feedrate in tons/hour in Figure 59. As expected, the amount of calcium compounds found at the precipitator inlet is a function of feedrate. Unexpected is the randomness of the data points with respect to particle size of the limestone. A regression analysis of Table XXXVIII data (22 sets) using the form of equation 21, where:

Y = Calcium oxide at precipitator inlet, tons/hours
X = Limestone feedrate to boiler, tons/hour

was performed. The data point from Test 10 was discarded, since it appears completely alien to the other test data points and there is no convenient way of determining whether it is bad or a real point. The following result was obtained:

$$Y = 0.12 + 0.071X \tag{38}$$

Correlation Coefficient = 0.91
F - Ratio Test Statistic = 99

This equation is limited to limestone feedrates in the range of 0 to 15 tons/hour.

The conclusions are that the amount of calcium oxide found at the precipitator inlet is significantly related to the feedrate in a linear manner, and neither the particle size of the limestone or the flue gas temperature at the dust collecting system is significant.

B. Examination of Particle Resistivity at the Precipitator Inlet as a Function of Calcium Oxide/Sulfur Ratio for High and Low Temperature Flue Gas

In Figure 60, the in-situ particle resistivity at the precipitator inlet has been plotted as a function of the CaO/S ratio in the particulate. The high and low flue gas temperature ranges are indicated separately. There appears to be no obvious correlation. However, in general, the lower gas temperature data seem, on the average, to result in a lower particle resistivity for the same CaO/S ratio. Nevertheless, it is concluded that nothing of significance is contained in Figure 60 relative to resistivity and CaO/S content of the particulate.

TABLE XXXVIII

SUMMARY OF DATA USED IN SECTION ON CHEMICAL ANALYSES (PPS.147-153)

Test No.	% CaO		Ratio CaO/S ESP Inlet	CaO At ESP Inlet (Tons/Hr)	(1) Gas Temp.	Precipitation Rate Parameter W(FPS)	Limestone Feedrate (tons/hr)	(2) Type Limestone	Particle Resistivity (3) Ohm-Cm
	MC Inlet	ESP Inlet							
2	30.8	28.6	4.1	0.48	H	0.24	7.55	F	1.2×10^{12}
6	33.0	30.0	4.9	0.64	H	0.03	11.60	F	5.6×10^{11}
8	33.3	31.4	4.4	0.91	L	0.35	11.15	F	1.6×10^{11}
9	--	4.5	3.0	0.05	L	0.34	0	-	3.8×10^{11}
10	--	23.5	3.8	0.43	L	0.43	16.75	C	6.7×10^{11}
11	--	31.6	6.4	1.03	H	0.26	15.25	C	6.5×10^{11}
14	35.6	33.9	6.0	1.19	H	0.33	14.10	C	8.9×10^{11}
15	36.7	34.7	5.3	1.08	L	0.29	14.45	C	1.4×10^{11}
18	--	33.6	7.0	0.69	H	0.17	9.15	F	5.6×10^{11}
19	--	1.4	3.5	0.04	L	0.41	0	-	2.8×10^{11}
20	--	2.2	3.7	0.08	H	0.58	0	-	1.8×10^{11}
21	--	1.1	2.7	0.02	L	0.44	0	-	1.4×10^{11}
22	--	5.6	7.0	0.13	H	0.36	0	-	1.8×10^{11}
23	--	5.9	5.4	0.14	H	0.13	1.84	F	3.7×10^{12}
24	--	18.8	8.9	0.47	H	0.15	3.45	F	2.9×10^{12}
25	--	26.0	4.8	0.80	L	0.50	10.55	C	1.4×10^{12}
26	--	30.8	6.2	0.59	H	0.17	7.05	F	2.4×10^{11}
27	--	28.8	7.4	0.60	L	0.26	6.45	F	1.5×10^{11}
28	--	38.6	9.9	1.12	H	0.29	11.15	F	5.9×10^{12}
29	--	28.8	7.4	0.78	L	0.27	6.25	F	4.3×10^{11}
30	--	27.2	6.5	0.84	H	0.18	6.30	F	9.0×10^{12}
32	27.7	27.7	4.1	1.11	H	0.48	8.50	C	8.3×10^{11}
33	25.5	26.3	4.5	0.75	L	0.43	7.85	C	9.1×10^{11}

(1) H = 290 to 320°F
(1) L = 240 to 260°F

(2) F = 50% by weight less than 6 microns
(2) C = 50% by weight less than 17 microns
(3) In-Situ at Precipitator Inlet

Figure 59

CALCIUM OXIDE AT ELECTROSTATIC INLET AS A FUNCTION OF LIMESTONE FEEDRATE TO THE BOILER

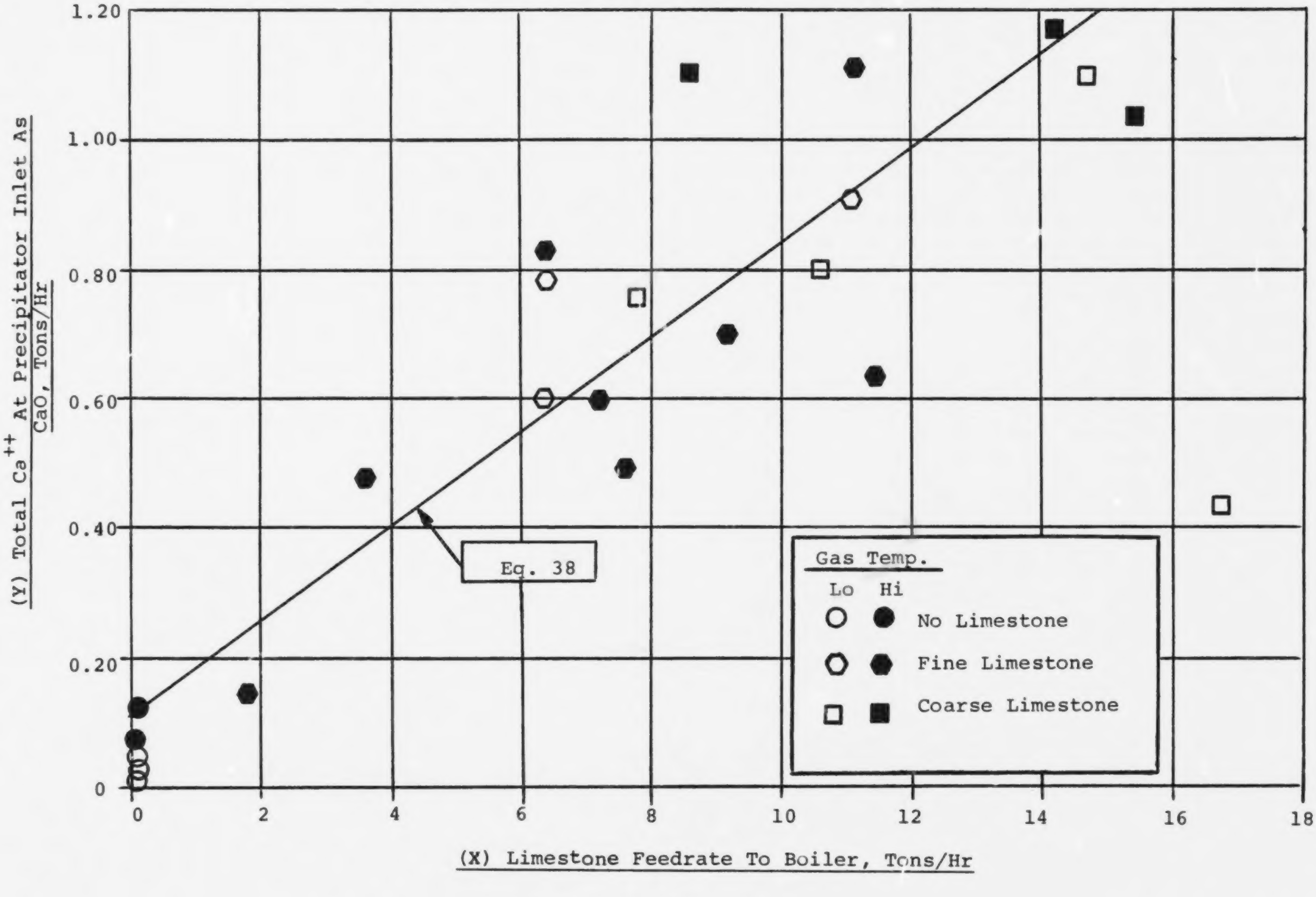
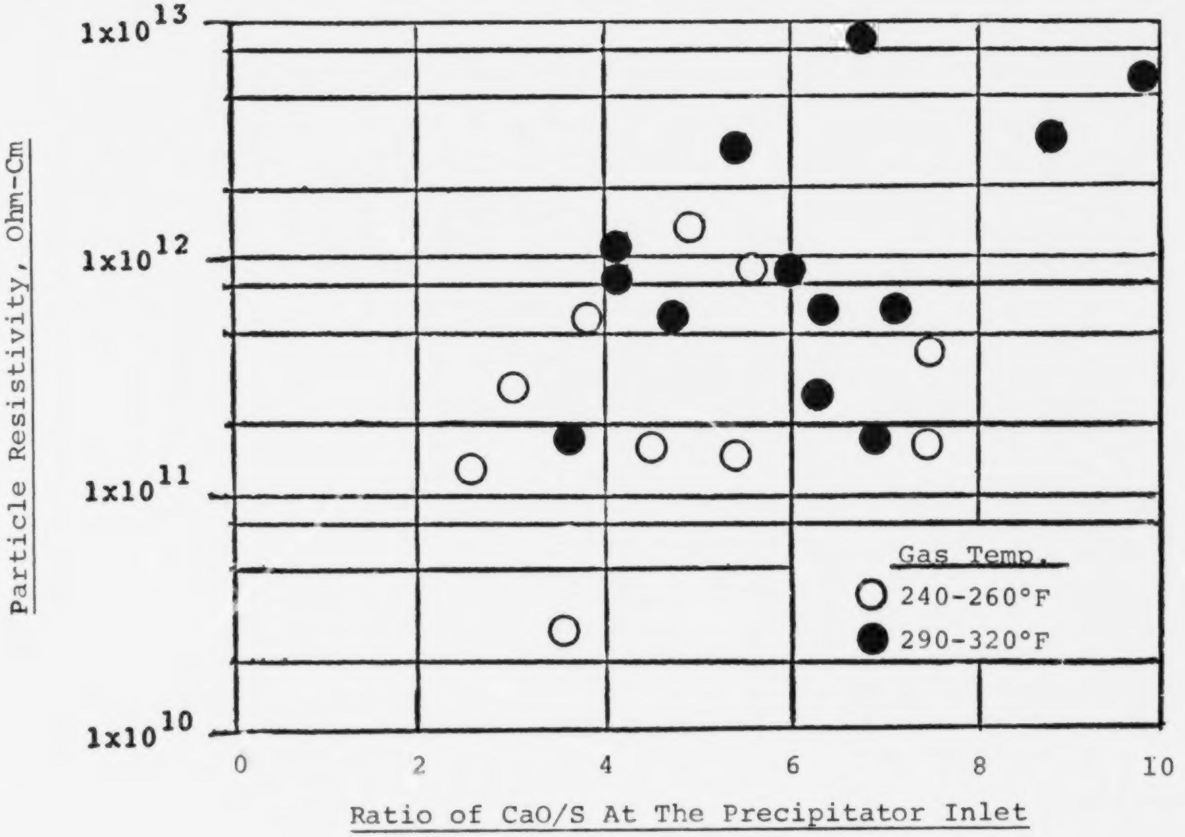


Figure 60

PARTICLE RESISTIVITY AS A FUNCTION OF THE CaO/S RATIO AT THE PRECIPITATOR INLET



Generally, the bulk chemical composition of the particulate and the performance of the precipitator elude correlation. An extensive research program into the chemical composition and physical nature of the particle surface is required.

5. Review of Optical Sensor Data

A proprietary Research-Cottrell, Inc., optical sensing instrument to determine dust concentrations was installed on the "B" side of Boiler No. 10 at Shawnee Station (see Figures 14 and 15). A simplified system diagram is shown in Figure 61. After standardizing with clean gas in measuring path and use of slope and intercept controls, the dust and reference signals are equal and of opposite polarity under a wide range of light source intensities when measuring path is clean.

$$E_A = -E_B \qquad (39)$$

With dirty gas, E_A decreases with increasing particle concentration and $-E_B$ remains constant.

Summing amplifier adds signals E_A and $-E_B$ and multiplies sum by its gain Gc to provide amplified difference signal to recorder.

$$\text{Recorder Reading} = Gc \quad E_A + (-E_B) \qquad (40)$$

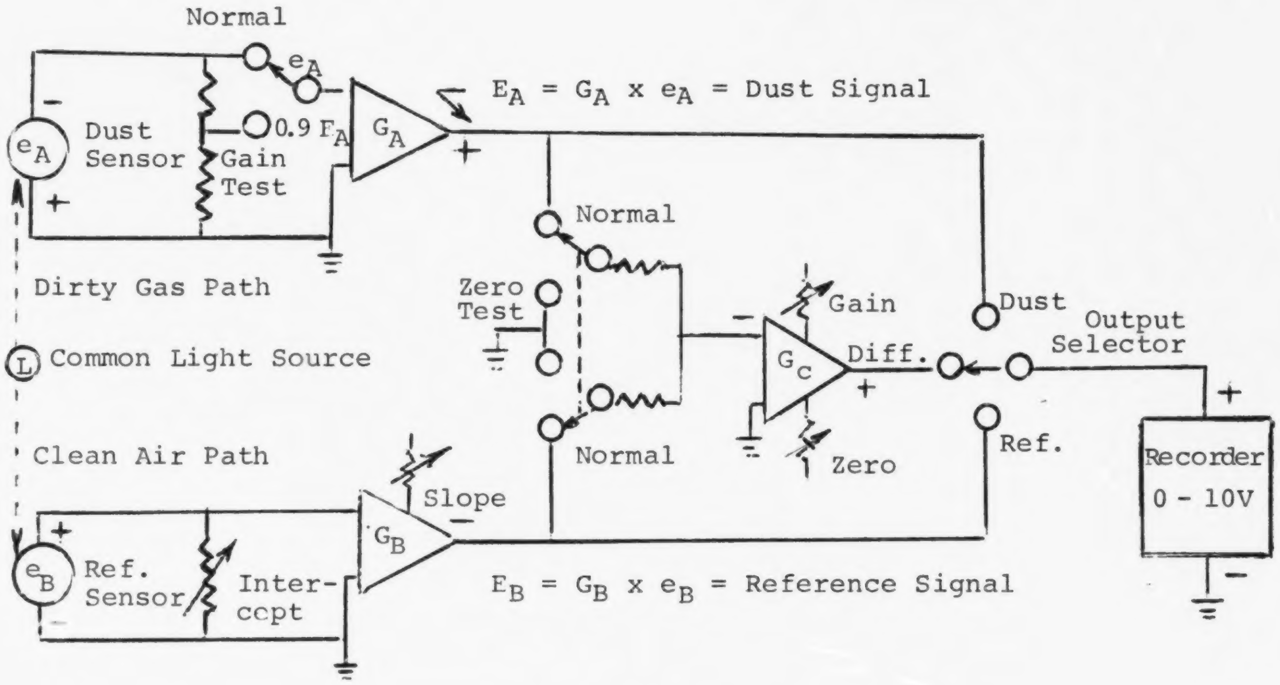
After an installation has been standardized, the reference signal $-E_B$ is equal to the maximum difference signal for that installation. For 0-5 Ringleman calibration, full-scale recorder voltage = (Gc) ($-E_B$). Maximum summing amplifier output is limited to about 13 volts.

The instrument was operative during the first CES and second TVA test series. Component failure (signal amplifier) during the second CES test series aborted further use of the instrument. Since all TVA tests were conducted on the "A" side, the correlation of nearly all the dust loadings with optical readout data are only quantitative. (Assumes comparable performance of the "A" and "B" side precipitators.) Table XXXIX summarizes data taken from the recorder charts during the first CES test series and the second TVA test series. A plot of the results (Figure 62) shows a fair correlation between the recorder chart reading (millivolts) and the precipitator outlet loading (grains/SCF). A critical consideration noted in the use of the optical sensor was the necessity for cleaning the lenses of the monitor periodically (at least daily). This requirement is evidenced by the two separate curves shown in Figure 62.

Figure 63 is a typical section of the optical sensor recorder chart showing various boiler and dust collector operating modes, e.g. coal firing only, response when additive is started and stopped, precipitator rapping puffs, boiler soot blowing, etc. This particular section of chart covers the time period beginning about 8:30 a.m. on July 1, 1970, and running continuously til about 3:00 p.m. on July 3, 1970. During this time period, TVA was running tests 37 through 44 from their second test series on the "A" side precipitator. Pertinent operating conditions are noted on the chart (Figure 63, pages F-151 through F-157). As can be seen on this chart, the optical sensor provides a good qualitative indication of boiler and dust collecting equipment operation. However, additional refinements and evaluation are necessary for its modification into a quantitative particulate monitoring instrument.

FIGURE 61

SIMPLIFIED SYSTEM DIAGRAM OF THE RESEARCH-COTTRELL, INC. PROPRIETARY OPTICAL SENSOR



Reference Amplifier

TABLE XXXIX

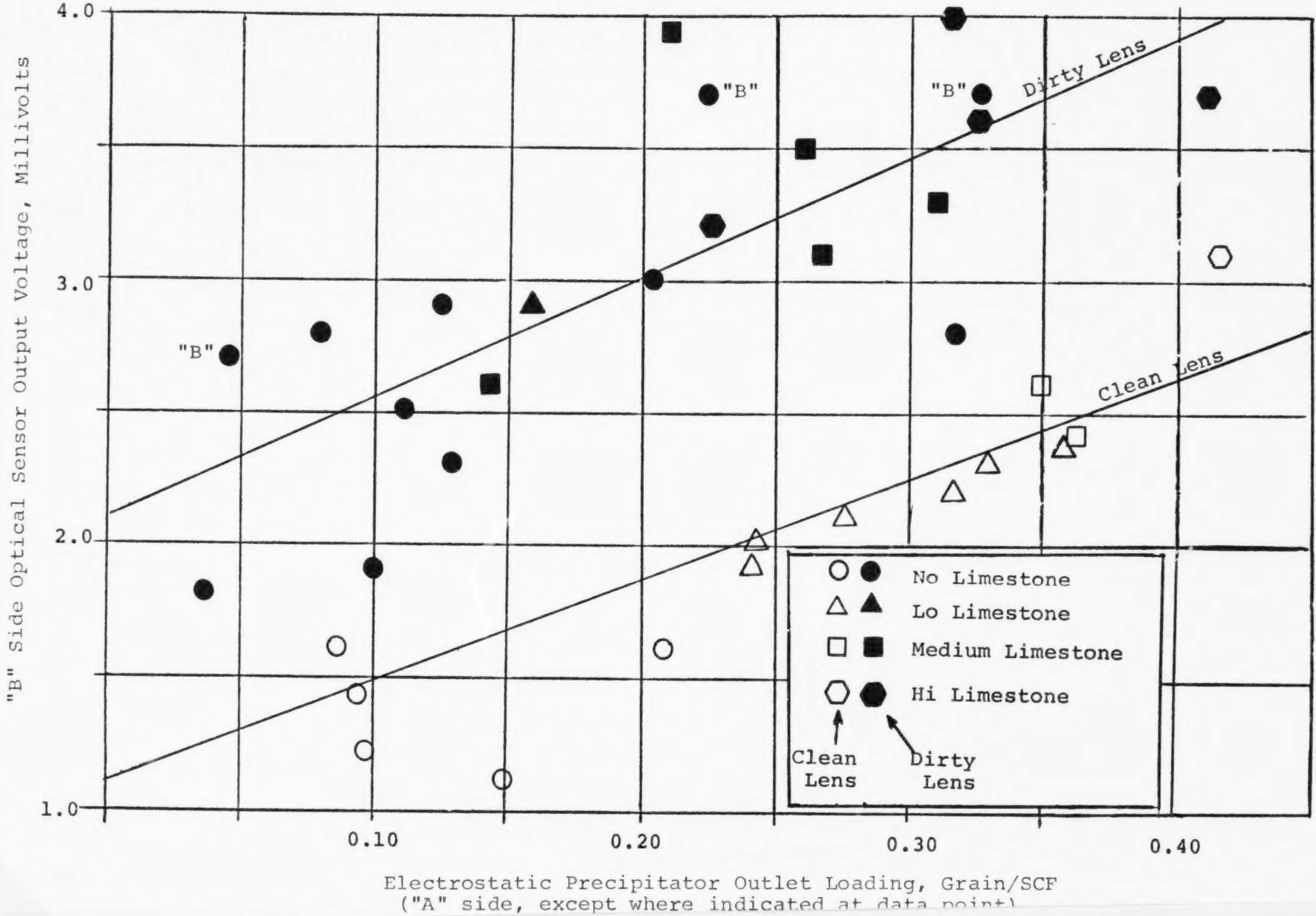
DATA TAKEN FROM THE OPTICAL SENSOR RECORDER CHARTS

Test No.	Chart Reading (Millivolts)	ESP Outlet Loading (gr/SCF)	Type Firing	Condition of Optical Sensor Lenses	Lime-stone Addition Rate[(1)]
1A(CES)	1.8	0.036	Coal	Dirty	0
2A	2.8	0.321	↓	↓	↓
5A	2.5	0.112	↓	↓	↓
3B	3.7	0.227	↓	↓	↓
4B	3.7	0.328	↓	↓	↓
5B	2.7	0.045	↓	↓	↓
38(TVA)	3.1	0.270	Coal + Additive	↓	Medium
39	3.7	0.416	↓	↓	High
40	3.0	0.207	Coal	↓	0
42	2.9	0.126	↓	↓	0
43	3.5	0.263	Coal + Additive	↓	Medium
44	4.0	0.319	↓	↓	High
46	2.8	0.080	Coal	↓	0
47	3.3	0.313	Coal + Additive	↓	Medium
48	3.6	0.329	↓	↓	High
50	1.9	0.099	Coal	↓	0
51	2.6	0.146	Coal + Additive	↓	Medium
52	3.2	0.228	↓	↓	High
54	1.1	0.49	Coal	Clean	0
55	2.4	0.362	Coal + Additive	↓	Low
56	2.3	0.333	↓	↓	Low
58	1.6	0.087	Coal	↓	0
59	2.0	0.246	Coal + Additive	↓	Low
60	2.1	0.278	↓	↓	Low
61	1.2	0.097	Coal	↓	0
62	1.9	0.243	Coal + Additive	↓	Low
64	1.4	0.094	Coal	↓	0
65	2.4	0.363	Coal + Additive	↓	Medium
66	3.1	0.418	↓	↓	High
68	1.6	0.211	Coal	↓	0
69	2.2	0.319	Coal + Additive	↓	Low
70	2.6	0.352	↓		Medium
72	2.3	0.129	Coal	Dirty	0
73	2.9	0.162	Coal + Additive		Low
74	4.0	0.213	↓		Medium

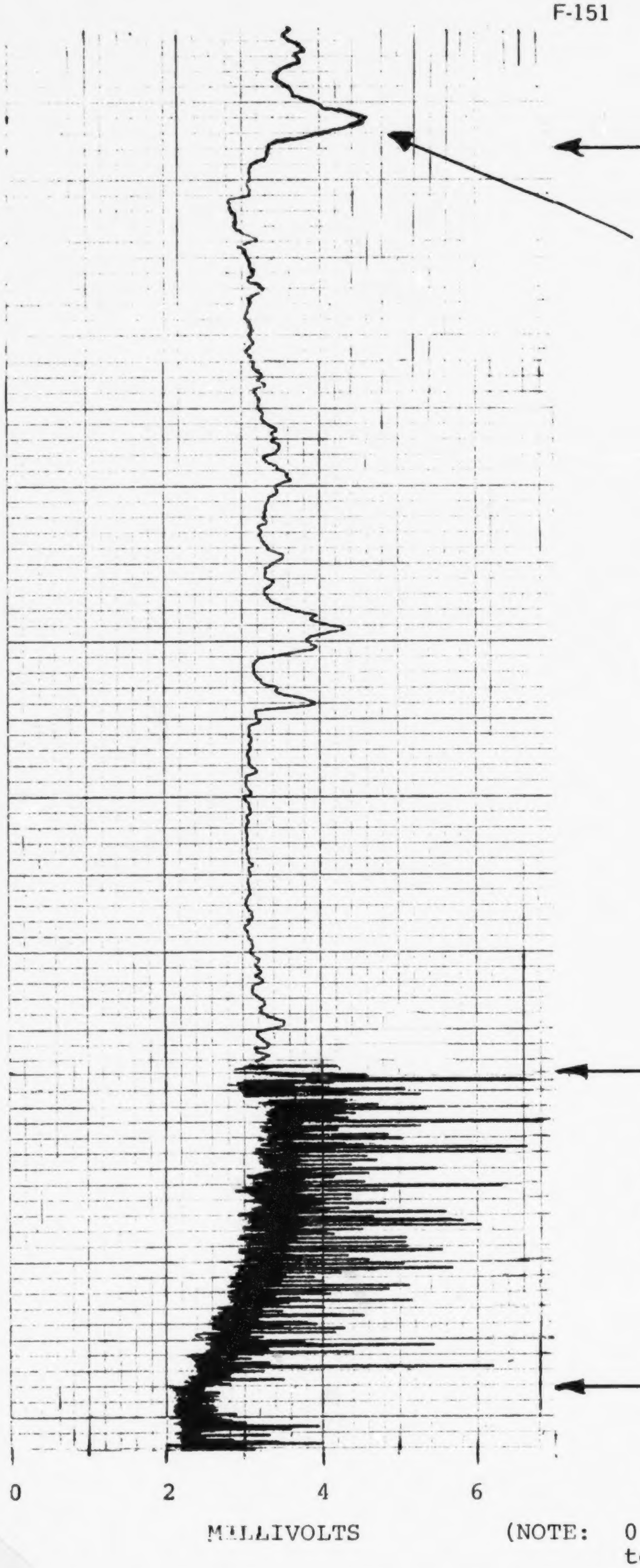
(1) Low = 1 to 3.5 tons/hour
Medium = 4.5 to 5.5 tons/hour
High = 9 to 10 tons/hour

FIGURE 62

DATA OBTAINED ON PARTICULATE LOADING USING AN OPTICAL MONITOR



F-151



10:43 AM

Peaks are rapping losses
from third section of
precipitator.

FIGURE 63

TYPICAL OPTICAL SENSOR CHART ON SHAWNEE #10 BOILER ("B" SIDE) WITH AND WITHOUT LIMESTONE INJECTION

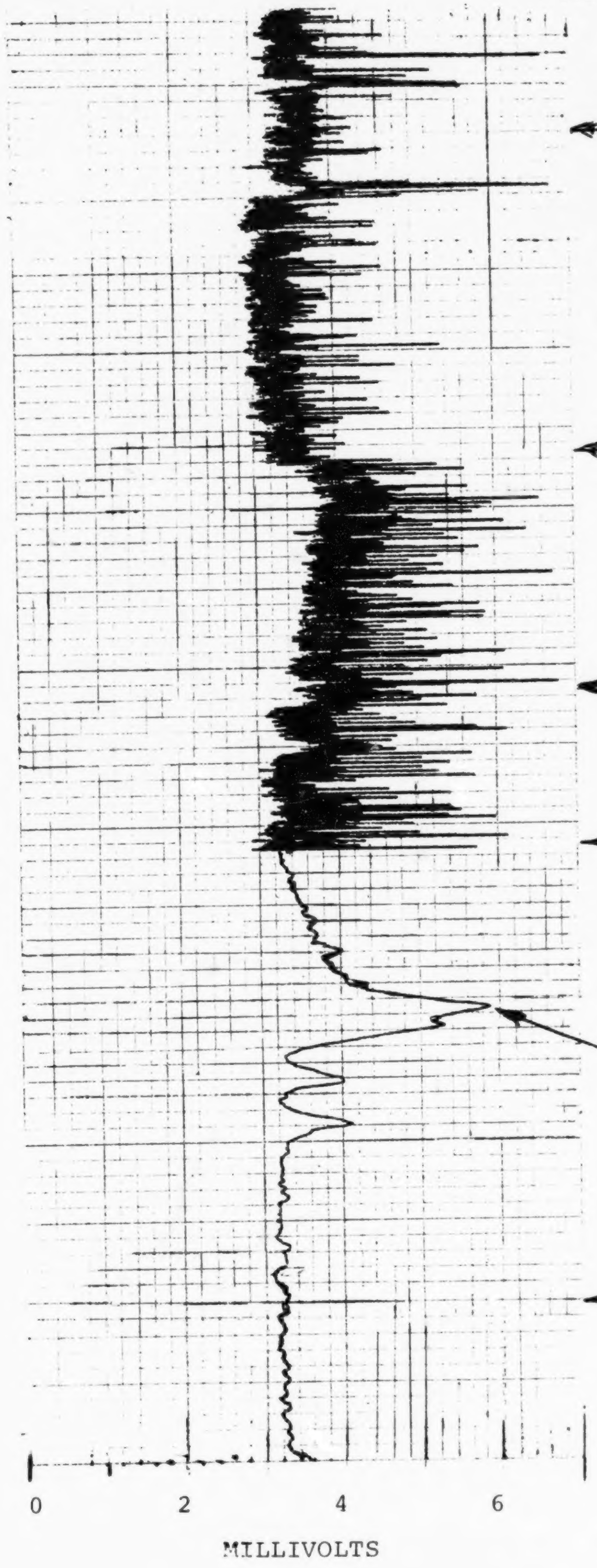
10:40 AM
Chart Speed = 2"/Minute

Boiler Load = 143 MW
Coal Ash = 18.3%
Coal Sulfur = 2.7%
Pptr. Eff. = 85.8%
Pptr. Outlet Loading = 0.27 gr/SCF

8:40 AM (July 1, 1970)
Start - Chart Speed = 1"/Hour

Limestone Feed Rate = 5.5 Tons/Hour

(NOTE: 0 to 10 millivolts equivalent
to 0 to 5 Ringelmann)



3:20 PM
Normal Coal Firing

Limestone Feed Off
1:20 PM

Boiler Load = 144 MW
Coal Ash = 15.4%
Coal Sulfur = 3.0%
Pptr. Eff. = 78.2%
Pptr. Outlet Loading = 0.42 gr/SCF

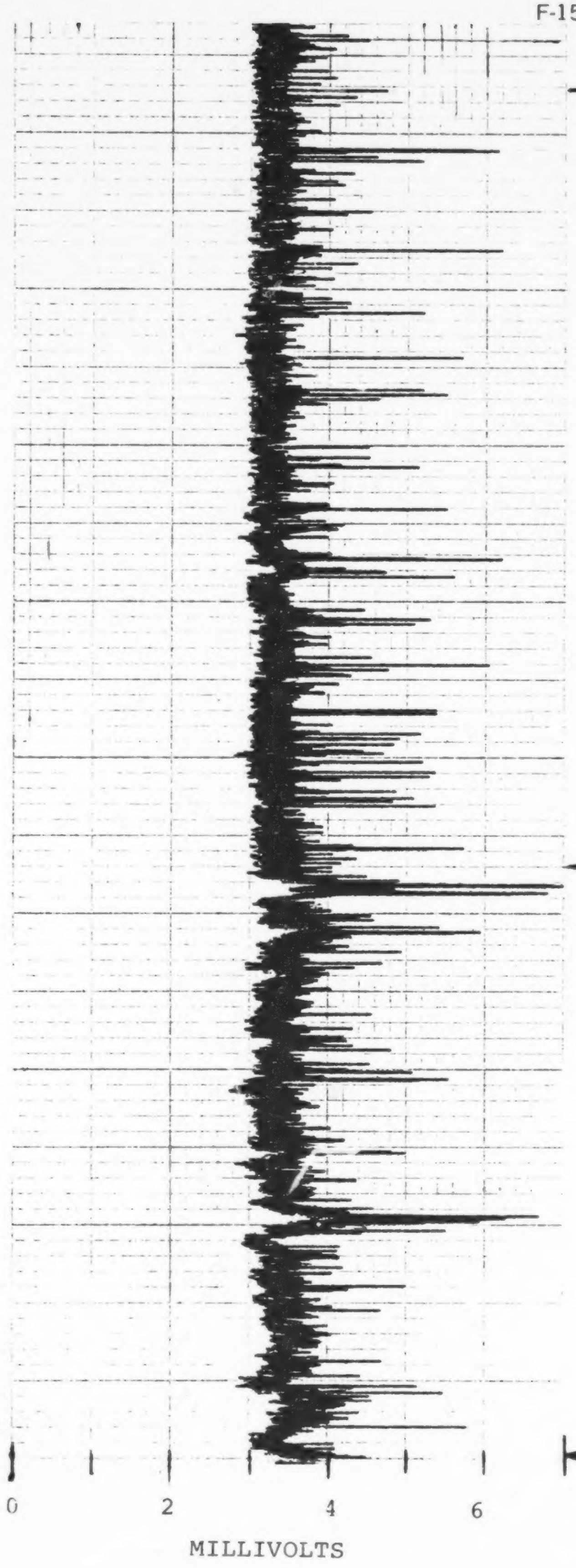
11:45 AM

Limestone Feed Rate = 10.0 tons/hou

10:45½ AM
Chart Speed = 1"/hour

Rapping Loss

10:44 AM (July 1, 1970)



1:00 AM (July 2, 1970)

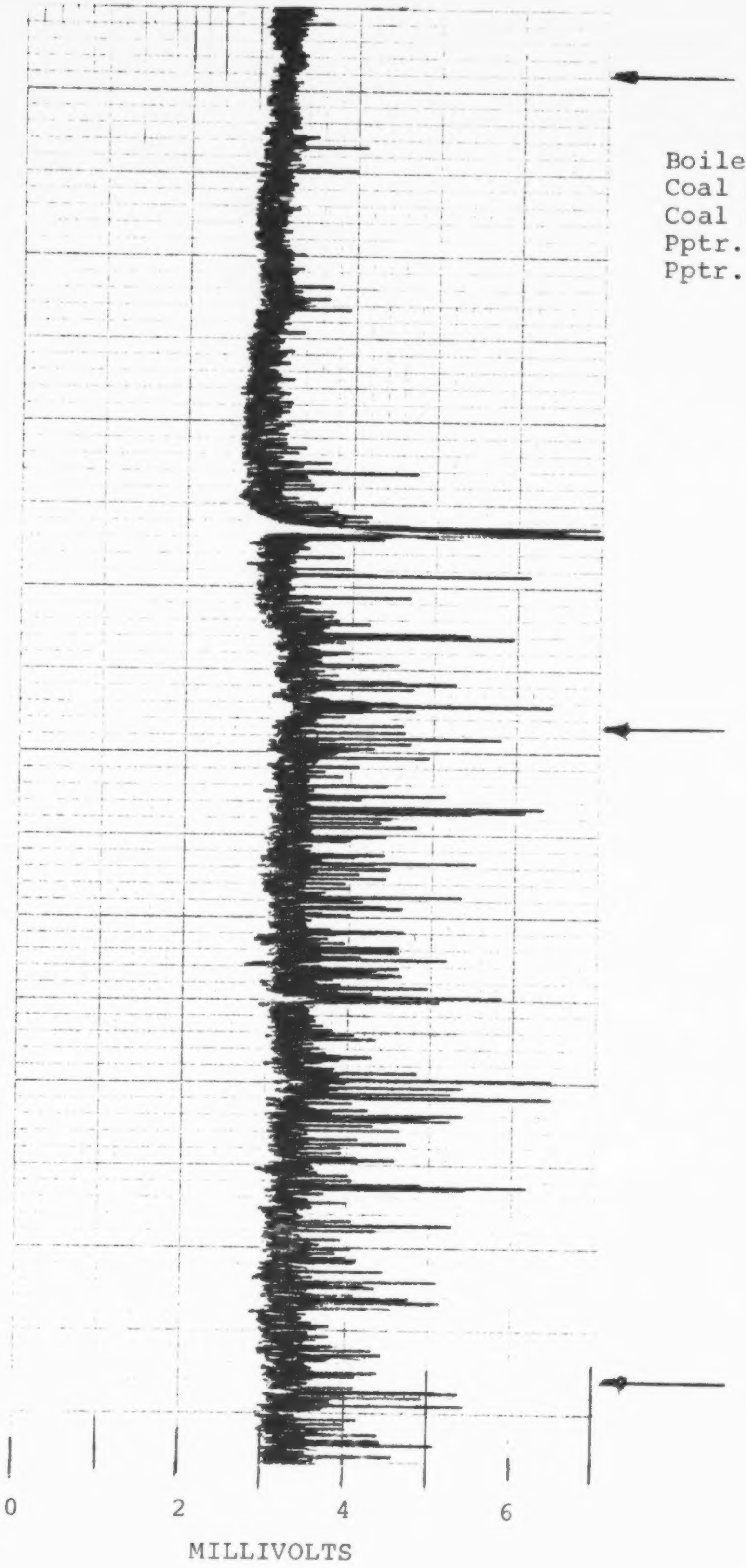
Normal Coal Firing
During This Period

Boiler Load = 144 MW

8:00 PM

Boiler Load = 144 MW
Coal Ash = 15.3%
Coal Sulfur = 2.8%
Pptr. Eff. = 79.8%
Pptr. Outlet Loading = 0.26 gr/SCF

4:15 PM (July 1, 1970)

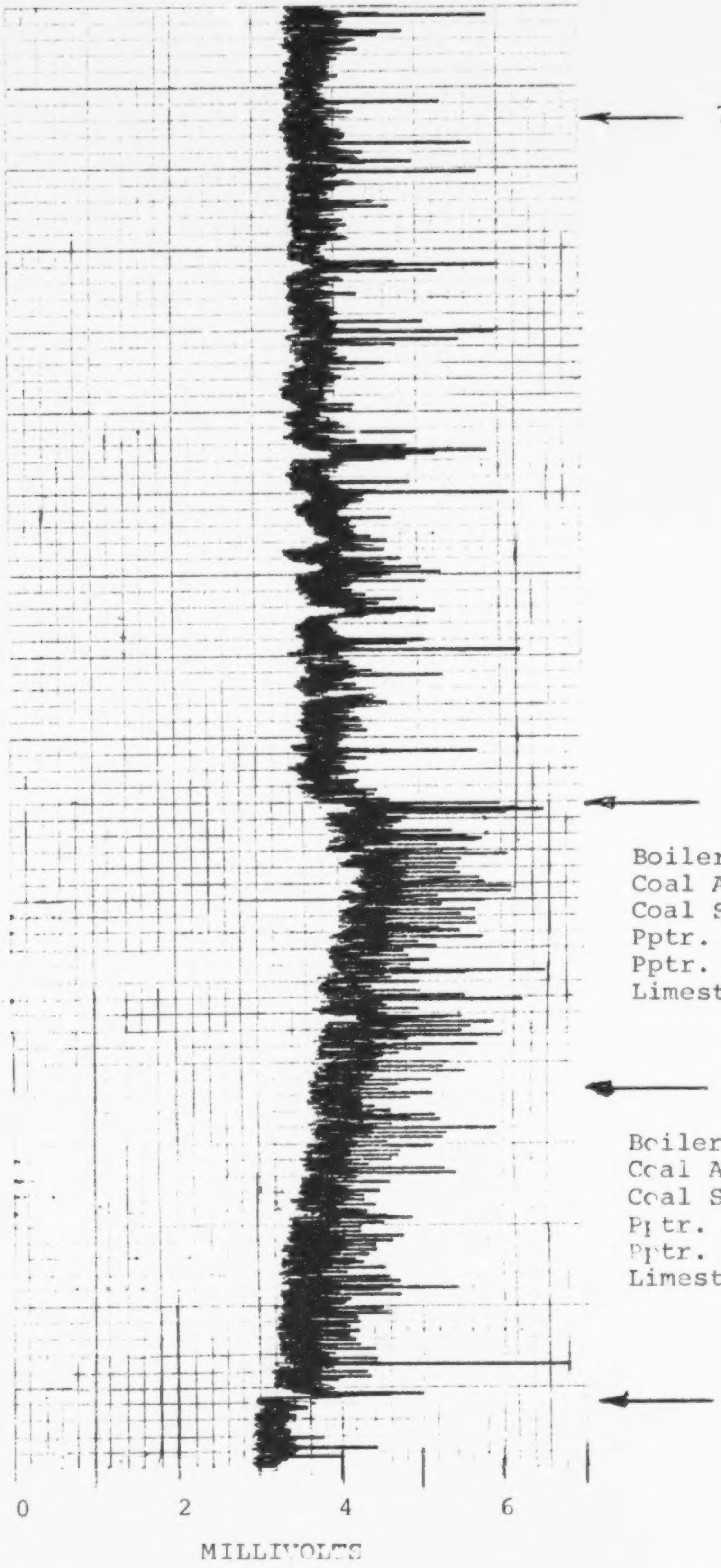


10:00 AM
Normal Coal Firing

Boiler Load = 142 MW
Coal Ash = 17.7%
Coal Sulfur = 3.4%
Pptr. Eff. = 91.3%
Pptr. Outlet Loading = 0.13 gr/SCF

6:00 AM

2:00 AM (July 2, 1970)



7:00 PM

Normal Coal Firing
During This Period

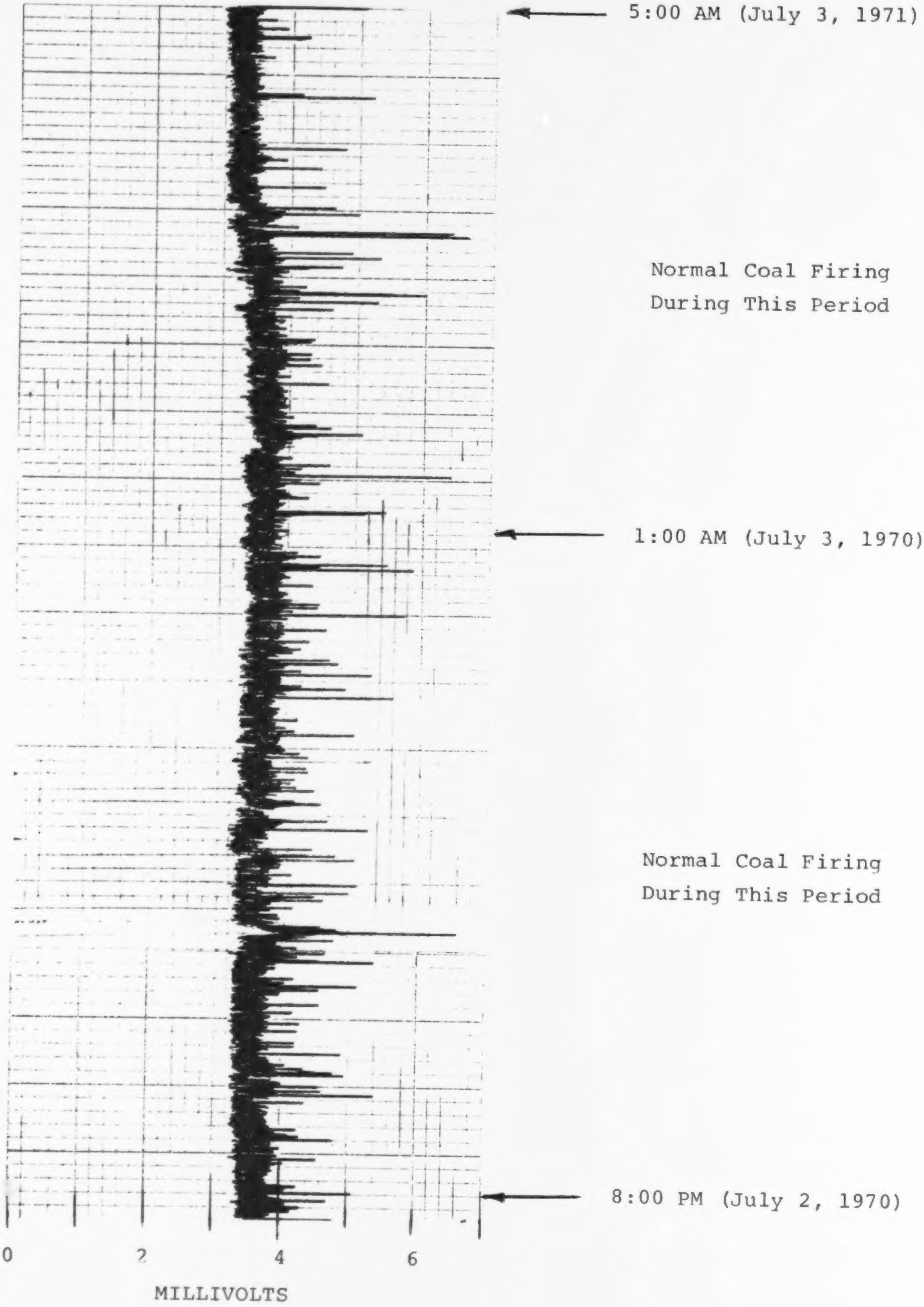
Limestone Feed Off
2:40 PM

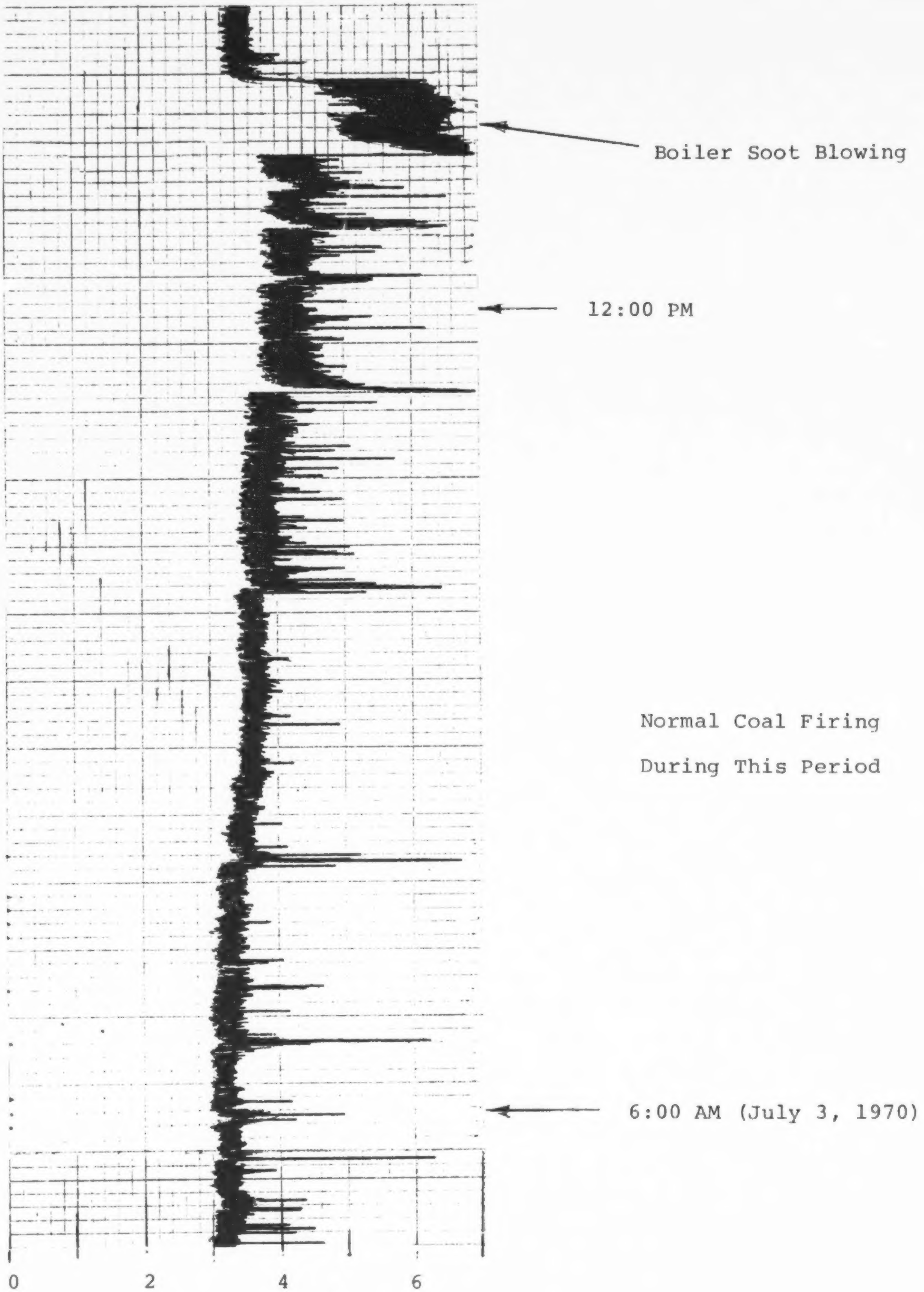
Boiler Load = 144 MW
Coal Ash = 15.9%
Coal Sulfur = 2.7%
Pptr. Eff. = 85.3%
Pptr. Outlet Loading = 0.32 gr/SCF
Limestone Feed Rate = 9.5 Tons/Hour

12:50 PM

Boiler Load = 143 MW
Coal Ash = 16.1%
Coal Sulfur = 3.0%
Pptr. Eff. = 82.7%
Pptr. Outlet Loading = 0.26 gr/SCF
Limestone Feed Rate = 4.5 Tons/Hour

10:55 AM (July 2, 1970)


5:00 AM (July 3, 1971)
Normal Coal Firing During This Period
1:00 AM (July 3, 1970)
Normal Coal Firing During This Period
8:00 PM (July 2, 1970)
0
2
4
6
MILLIVOLTS


Boiler Soot Blowing
12:00 PM
Normal Coal Firing
During This Period
6:00 AM (July 3, 1970)
0
2
4
6
MILLIVOLTS

VII. TECHNO-ECONOMIC EVALUATION OF VARIOUS ALTERNATIVES FOR MAINTAINING THE STACK EMISSION RATE WITH LIMESTONE INJECTION EQUIVALENT TO A BASELINE CONDITION OF NO LIMESTONE INJECTION

The baseline conditions for no limestone injection used in this evaluation were determined by first selecting a coal having between 2.5 and 3.5% sulfur as being typical of that burned at the Shawnee Station. Then the boiler and electrostatic precipitator operating parameters were established by averaging test results obtained by the Tennessee Valley Authority in 1970 when this type of sulfur coal was fired. (Table XL summarizes these results.) The mechanical collector performance was established by averaging test results obtained by Cottrell Environmental Systems in 1969. (Table V.) The average baseline conditions obtained in this manner for Shawnee Station were (1) a boiler burning 2.8% sulfur and 15.5% ash coal at a rate of 63.3 tons/hour, resulting in a 141 megawatt load and a flue gas volume of 570,000 cfm at 309° F having a particulate loading of 3.32 grains/SCF (70° F and 29.9"Hg) at the dust collector inlet; (2) a particulate collection system consisting of a 57.4% efficient cyclone followed by a 91.3% efficient electrostatic precipitator (precipitation rate parameter of 0.39 FPS) resulting in an overall efficiency of 96.3% and a stack emission rate of 0.122 grains/SCF or 412 pounds/hour.

For purposes of this evaluation, an injection stoichiometry of 2.0 moles of CaO/mole S in the coal was established.

Using the baseline condition of 63.3 tons/hour of 2.8% sulfur coal, a limestone injection rate of 11.1 tons/hour was calculated.

Five basic alternatives were considered in the techno-economic evaluation, i.e. size modification of the presently installed dust collecting system, use of a "hot" electrostatic precipitator, gas cooling ahead of the dust collecting system, gas conditioning ahead of the dust collecting system, and type of electrical energization for the precipitator.

1. Size Modification of the Presently Installed Dust Collecting System

Examination of the performance data of the mechanical collector without and with coarse or fine limestone injection shows no significant differences, i.e., the removal efficiency was essentially unaffected, ranging on the average between 50 and 60% removal. However, the particulate loading at the mechanical inlet and outlet will vary with the coal ash content and amount of additive injection. The mechanical outlet-electrostatic inlet loading, as a function of limestone feedrate, has been shown previously in Figure 46. The performance of the precipitator is significantly affected by the particle size of the limestone injected (Table XXX) with the coarse giving the higher precipitation rate parameter. Accordingly, the overall efficiency and the

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TABLE XL

SUMMARY OF 1970 TVA TEST RESULTS USED IN ESTABLISHING BASELINE BOILER AND PARTICULATE COLLECTOR OPERATING PARAMETERS FOR NO-LIMESTONE INJECTION

(1) Test No.	ESP Particulate Loading (gr/scf)		ESP Efficiency (%)	Flue Gas Temp. (^{o}F.)	Gas Volume (ACFMx10^{-3})	(2) Coal Analysis(%)		Pptn. Rate Parameter (FPS)	Boiler Load (MW)	Coal Firing Rate (tons/hr)
	Inlet	Outlet				Sulfur	Ash			
42	1.446	0.126	91.3	316	306	3.4	17.7	0.41	142	64.0
46	1.392	0.102	92.6	306	295	2.7	17.1	0.43	142	64.0
50	1.559	0.099	93.7	307	289	2.7	14.0	0.37	142	64.0
54	1.465	0.149	89.8	310	285	2.7	13.7	0.36	140	62.5
58	1.737	0.087	94.9	304	279	2.8	14.0	0.46	142	64.0
61	1.119	0.097	91.6	304	302	2.6	13.8	0.42	141	63.0
64	1.449	0.094	93.4	310	294	3.1	14.2	0.44	142	64.0
68	1.463	0.214	85.6	309	287	2.5	14.8	0.31	140	62.5
72	1.119	0.129	88.5	311	227	2.5	20.2	0.27	139	62.0
Avg.	1.416	0.122	91.3	309	285	2.8	15.5	0.39	141	63.3

(1) Tests run with no limestone injection and a precipitator sparking rate of about 150/min.

(2) Tests with coal sulfur between 2.5 and 3.5%.

resulting emission rate from the stack will be a significant function of the electrostatic precipitator performance and inlet particulate loading only. For purposes of comparing required size modifications for the baseline no injection, and the coarse or fine limestone injection cases, it has been assumed that the precipitation rate parameter is unaffected in the 290 to 310°F flue gas temperature range. Using data contained in Figures 19 or 46, and Tables XXX or XL, a precipitator size modification and cost evaluation has been made for the presently installed dust collecting system. Results are summarized in Table XLI.

The estimated precipitator capital cost (installed) of \$5.25/ft^2 of collecting plate area includes the base precipitator flange to flange, support steel, insulation, foundations, and labor to supervise and install the precipitator. It does not include the ash handling system and any mark-up for profit which can vary widely, depending upon the vendor.

2. Installation of a "Hot" Precipitator

The use of a straight "hot" precipitator at 600°F (air heater inlet gas temperature) would eliminate the dust resistivity problem and, whether limestone is injected or not, the precipitation rate parameter would be constant, e.g., in the range of 0.3 FPS. Adjusting the baseline gas volume to 600°F and eliminating the mechanical collector (assume 57.4% efficient on fly ash and 55% efficient on fly ash plus limestone reaction products), the new precipitator inlet gas volume and particulate loadings would be 788,000 ACFM and 3.32 grains/SCF for no injection, and 6.88 grains/SCF for 2X stoichiometric injection. On the basis of the above assumptions, a "hot" precipitator has been sized and costed that would reduce particulate emissions to 0.122 grains/SCF. Results are summarized in Table XLII.

3. Gas Cooling Ahead of the Dust Collecting System

With an alkaline additive injected into the gas stream which removes most of the sulfur trioxide by chemical reaction, it is possible to design a dust collecting system to operate at about 250°F without danger of corrosion due to sulfuric acid condensation. Since the present system, normally operates about 300°F, it would be necessary to cool the gas about 50°F. This could be accomplished by the addition of more heat transfer surface or possibly by injection of atomized water with the added benefit of moisture conditioning. Table XLIII summarizes results of an evaluation using gas cooling ahead of the dust collecting system.

4. Gas Conditioning Ahead of the Dust Collecting System

The use of conditioning agents, such as sulfur trioxide (sulfuric acid), to reduce dust resistivity and improve precipitator performance is well known. However, with the

TABLE XLI

SUMMARY OF ELECTROSTATIC PRECIPITATOR SIZE MODIFICATIONS AND COSTS FOR THE PRESENTLY INSTALLED DUST COLLECTING SYSTEM REQUIRED TO MAINTAIN A STACK EMISSION RATE EQUIVALENT TO BASELINE NO-LIMESTONE INJECTION

Condition	Baseline No Limestone Injection	Coarse Limestone Injection	Fine Limestone Injection
Flue Gas Temperature, °F.	309	309	309
Sulfur Feed Rate, tons/hr(1)	1.77	1.77	1.77
Limestone Feed Rate, tons/hr	0	11.1	11.1
Injection Stoichiometry, moles CaO/mole S	0	2	2
Gas Volume, ACFM	570,000	570,000	570,000
Pptr. Inlet Loading, gr/cf(2) @ 70F & 29.9"Hg	1.416	3.10	3.10
Pptr. Outlet Loading, gr/cf @ 70F & 29.9"Hg	0.122	0.122	0.122
Pptr. Efficiency, %	91.3	96.1	96.1
Power Density, KW/1000 ft^2 (3)	0.70	0.23	0.15
Precipitation Rate, FPS(4)	0.39	0.36	0.16
Precipitator Area, Ft^2	59,400	85,800	193,000
Pptr. Size Factor X Base Size	1.0	1.45	3.25
Pptr. Capital Cost (Installed)(5) \$/KW	2.21	3.21	7.20

(1) Based on 63.3 tons/hr of coal @ 2.8% sulfur.

(2) Taken from Figure 46 or Table XL.

(3) Taken from Figure 19 or Table XXX.

(4) Taken from Table XL or XXX.

(5) Based on a boiler load of 141 megawatts and precipitator capital cost (installed) as defined in the text. (\$5.25/ft^2 collecting plate area).

TABLE XLII

SUMMARY OF THE "HOT" PRECIPITATOR SIZING AND COSTING FOR SHAWNEE STATION BOILER #10 WITH AND WITHOUT LIMESTONE INJECTION

(Straight Precipitator)

Condition	No Limestone Injection	Coarse or Fine Limestone Injection
Flue Gas Temperature, °F.	600	600
Sulfur Feed Rate, tons/hr	1.77	1.77
Limestone Feed Rate, tons/hr	0	11.1
Injection Stoichiometry, moles CaO/mole S	0	2
Gas Volume, ACFM	788,000	788,000
Pptr. Inlet Loading, gr/cf @ 70F & 29.9"Hg	3.32	6.88
Pptr. Outlet Loading, gr/cf @ 70F & 29.9"Hg	0.122	0.122
Precipitator Efficiency, %	96.3	98.2
Precipitator Rate, FPS	0.30	0.30
Precipitator Area, Ft^2	144,500	176,000
Precipitator Capital Cost (1) (installed), $/KW	5.85	7.10

(1) Based on a boiler load of 141 megawatts and precipitator capital cost (installed) of $5.70/$ft^2$ collecting plate area.

TABLE XLIII

SUMMARY OF GAS COOLING AS AN OPTION FOR COARSE OR FINE LIMESTONE INJECTION

Condition	Coarse Limestone Injection	Fine Limestone Injection
Flue Gas Temperature, °F	250	250
Sulfur Feed Rate, Tons/Hour	1.77	1.77
Limestone Feed Rate, Tons/Hour	11.1	11.1
Injection Stoichiometry, Moles CaO/Mole S	2	2
Gas Volume, ACFM	526,000	526,000
Pptr. Inlet Loading, gr/cf @ 70°F & 29.9"Hg	3.10	3.10
Pptr. Outlet Loading, gr/cf @ 70°F & 29.9"Hg	0.122	0.122
Precipitator Efficiency, %	96.1	96.1
Power Density, KW/1000 Ft^2	0.51	0.30
Precipitation Rate, FPS	0.41	0.31
Precipitation Area, Ft^2	69,300	92,300
Pptr. Capital Cost (Installed)(1) $/KW	2.58	3.44

(1) Based on a boiler load of 141 megawatts and precipitator capital cost (installed) of $5.25/ft^2 collecting plate area.

addition of large amounts of alkali, the conditioning effect may be cancelled. Nevertheless, if the additive surface has been sulfated ahead of the conditioning injection point, it may still be possible to improve precipitator performance by sulfur trioxide addition. On this basis, and assuming the precipitation rate with coarse or fine limestone injection will be improved to the no limestone level, a size and cost of a precipitator for limestone injection has been determined. At 309°F, with a precipitation rate of 0.39 FPS and a required efficiency of 96.1% for 570,000 ACFM, the collecting area is 70,000 ft^2. The precipitator capital cost (installed) per kilowatt generated is $2.94.

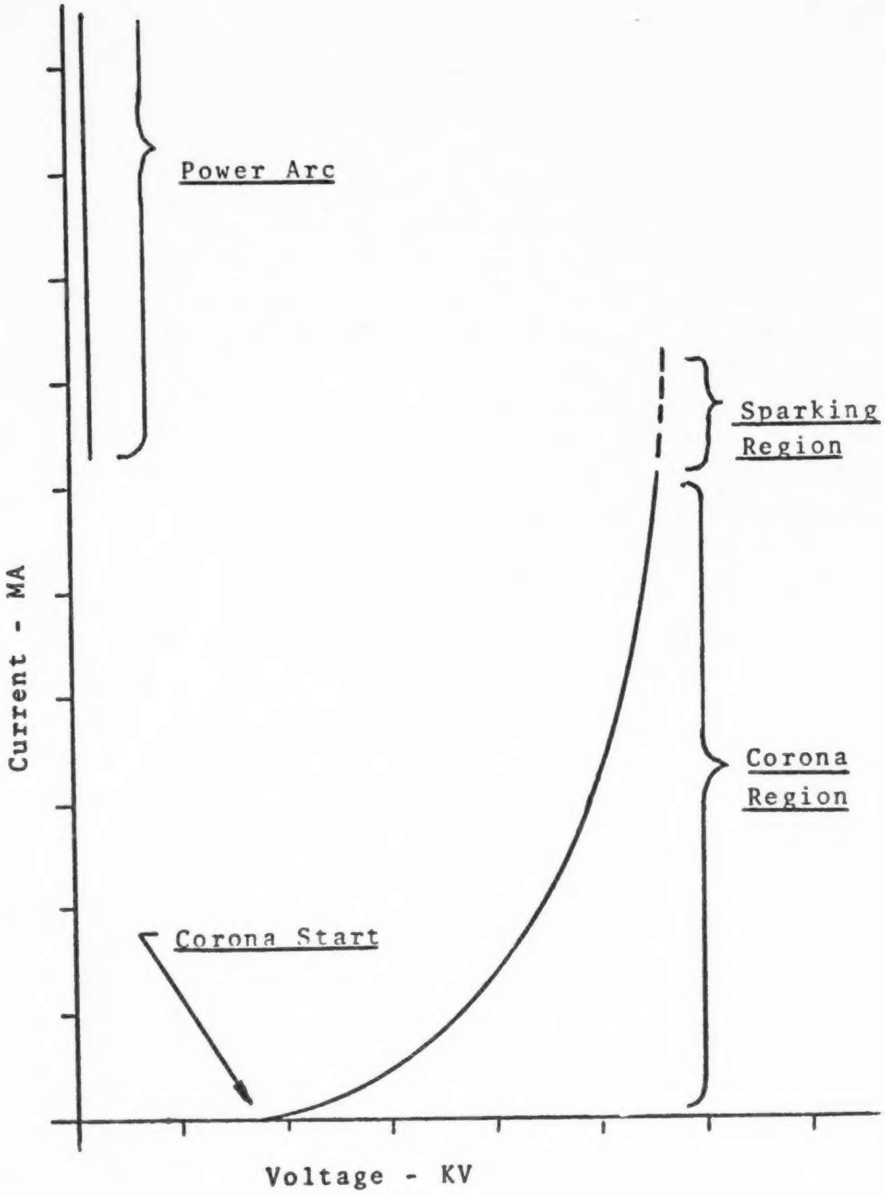
5. Electrical Energization of the Precipitator

Basically the precipitator electrical system consists of the electrical load (precipitator), the power conversion equipment (high voltage power supply), and the power control equipment (low voltage control). Single stage industrial gas-cleaning precipitators are generally energized by H-V direct current which is derived from commercial alternating current power supply lines. Power conversion is accomplished in the H-V power supply by means of A-C voltage transformation and H-V rectification, usually without ripple filtering. Precipitator energization is controlled by the L-V control which regulates electrical input to the H-V power supply. The combination of an H-V power supply and its associated L-V control is commonly called an electrical set. Most large precipitators are internally subdivided to provide a number of isolated electrical sections or collecting zones. These precipitator subdivisions are made longitudinally, transversely, or in a longitudinal/transverse arrangement in relation to precipitator gas flow stream. Each section or collecting zone represents a discrete electrical load requiring an electrical set for energization.

A single-stage precipitator is essentially a gaseous electrical discharge device which in most cases is operated at pressures close to atmospheric and temperatures ranging from ambient to several hundred degrees. As such it has a nonlinear voltage-current characteristic with discontinuities as illustrated in Figure 64. Except for insulator leakage, negligible current flows until sufficient voltage exists between the discharge electrode and the collecting electrode to initiate a corona discharge (corona starting voltage). Increasing the voltage above the corona start point causes precipitator current to rise sharply until the voltage becomes sufficiently high to cause random, momentary sparkover "snaps" between the discharge electrode and the collecting surface (sparking region). At this point the gaseous discharge is highly unstable and can readily transfer from the sparking mode to the power arc mode. The power arc mode is characterized by sustained low voltage and heavy currents which are limited only by the power supply system impedance. The corona region just prior to and slightly into the sparking

FIGURE 64

TYPICAL PRECIPITATOR VOLTAGE VS CURRENT CHARACTERISTIC



region is the useful portion of the precipitator voltage-current characteristic for particulate collection. Fundamental research has shown that precipitator performance is initially dependent upon maintaining the highest possible voltage on the precipitator electrode system. It has also been shown that some benefits are gained by operation under controlled sparking conditions again due to higher operating voltage. Normally, the discharge electrode is operated with negative polarity because negative corona permits higher voltage operation before sparkover than positive polarity.

Basically, the voltage levels required are a function of the precipitator electrode geometry—including discharge electrode cross-sectional size and shape and the discharge wire to collecting surface spacing. The current flow, at a given voltage, is a function of the size of the precipitator section—being dependent upon the discharge electrode length and collecting surface area. In practice, corona voltage and current levels are further modified by plant operating conditions such as: type and concentration, temperature, and pressure; and electrode deposits and alignment.

Actual precipitator electrode configurations are selected to permit stable corona conditions and relatively high sparking voltages in addition to practical considerations of durability and economy. Since sparking voltage is generally governed by the closest discharge electrode to collecting electrode spacing, it has been found that electrical sectionalization of a large precipitator permits higher operating voltages and reduces dust loss due to an individual sparkover. Differences in particulate concentration throughout the precipitator also affect the corona and sparking characteristics. Thus, sectionalization permits each treating zone to be energized more closely to ideal levels for the particular zone.

Back corona is a description term applied to a very undesirable gaseous discharge phenomena which occurs in precipitators treating particulate matter having resistivities greater than $\sim 10^{10}$ ohm-cm. Under this condition, a corona discharge occurs on the dust layer on the collecting electrode as well as the discharge electrode.

With negative polarity, the typical electrical characteristic of the precipitator is drastically altered by back corona. The sparkover voltage for the precipitator is lowered to 50% or less than normal and a stable heavy-current, low-voltage discharge can occur. In this latter case, rated current flows at perhaps 30% or less of the voltage normally associated with the electrode structure. Needless to say, particulate collection falls far below design with back corona because of the low interelectrode voltage. Normal corona on the discharge electrodes appears as sharply defined tufts of light which lie along straight lines, formed by the wires. The back corona appears as more diffuse tufts of light randomly spread over the collecting electrode area.

Traditionally, back corona problems have been alleviated by: reducing particulate resistivity by process change; use of conditioning agents; and increased precipitator sectionalization. It has been found that back corona conditions can also be solved by controlling the voltage wave shape. This is possible since a time factor, quite analogous to that of a capacitor, is involved in the establishment of back corona. Thus, use of impulse voltages provides means to raise sparkover and peak operating voltage under back corona conditions.

Radar type pulse systems which provide sharply rising voltage pulses have been experimentally applied and found advantageous in high-resistivity problem areas. However, their commercial application has so far been precluded by: general lack of understanding, economy, apparatus complexity, and certain electrical component deficiencies.

As previously mentioned, large precipitators are normally subdivided into discrete electrical sections. Figure 65(a) shows typical precipitator energization arrangements for a sectionalized precipitator. The Figure 65(b) arrangement is often beneficial since gas inlet sections tend to operate at lower corona power levels (high voltage, low current, heavy sparking) as compared to gas outlet sections. Half-wave energization does have the disadvantage that dissimilar sections cannot be properly energized—the energization level is limited by the power section. Also it has been found in certain high-power electrical set arrangements (50 KW or larger sets) that a spark transient disturbance in one HW section can cause magnetic circuit unbalance which unduly prolong the disturbance.

During the present test program, all precipitator sections were energized full-wave. Possible performance improvement might be achieved by more sectionalization, half-wave or pulse energization. Additional testing is required to establish this.

FIGURE 65

TYPICAL PRECIPITATOR ENERGIZATION ARRANGEMENTS

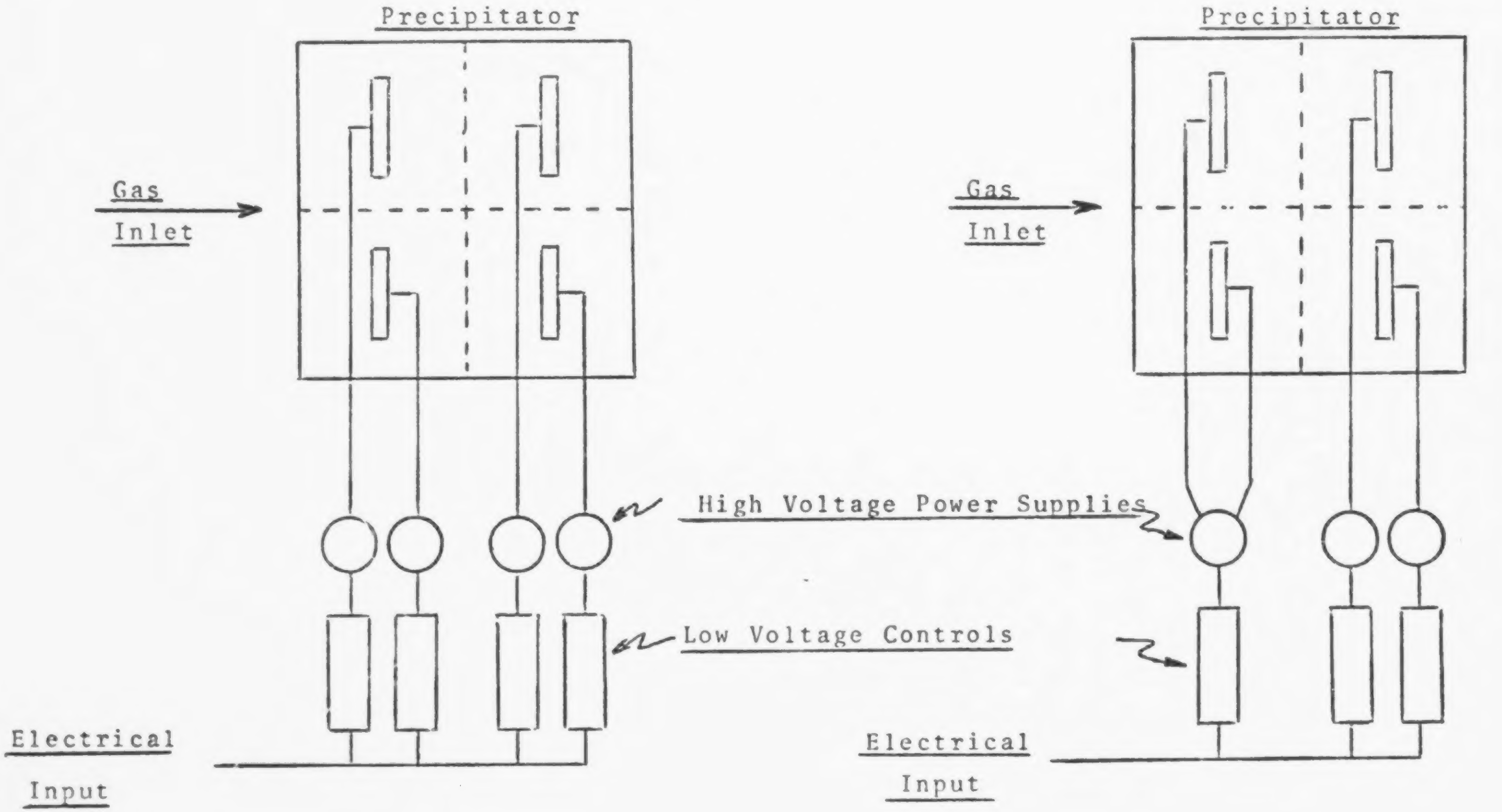


Figure 65(a)

All Sections Full-Wave

Figure 65(b)

Half-Wave Inlet Sections

Full-Wave Outlet Sections

VIII. RECOMMENDATIONS

Although the use of dry limestone injection into the boiler hot gases, as a means of significantly reducing sulfur oxide emissions, appears to be only a stop gap measure useful in existing power plant boilers, the deleterious affects on electrostatic precipitator performance are analogous to those experienced when burning low sulfur coals, particularly the sub-bituminous western coals. In view of this more general problem, it is recommended that further experimental work be performed.

1. The present test program has clearly shown the effect of corona input power density on the precipitation rate parameter. The most critical variable that determines corona power is the particulate resistivity. There are basically four ways of combating high resistivity, i.e., use of a large precipitator, use of some form of conditoning such as moisture, ammonia, sulfur trioxide, etc., control the flue gas temperature entering the precipitator, or change the voltage waveform of electrical energization and/or increase sectionalization. The first three have been the subject of numerous investigations, however, the latter, although known to be effective, has never been really investigated using a carefully planned experimental program. Accordingly, it is recommended that this be done using full-wave, half-wave and pulse energization along with variations in sectionalization.

2. The fact that precipitator performance during the special low sulfur coal tests of this program was as good or better than when firing the higher sulfur coals points out the need for establishing additional means other than coal sulfur for predicting expected performance. Recent experimental work by the Bureau of Mines[14] has correlated the ratio of $\frac{MgO + CaO}{Na_2O + SO_3}$ in the ash to resistivity. Also, the Na_2O of the ash alone appears to be significant.

   It is recommended that experimental work relating precipitator performance to coal ash and fly ash chemical constituents be performed.

3. Recent state particulate emission codes are establishing stack opacity as a means of determining compliance. Therefore, it is recommended that further work in quantifying an optical sensor, such as the Research-Cottrell instrument, be undertaken.

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G-i

APPENDIX G

Limestone Injection Effects on Disposal Water Quality

APPENDIX G

Introduction

Increased demand for a high quality environment and the resulting influx of new pollution abatement technology has focused added attention on the management of the interrelated aspects of land, water, and air pollution control. It is becoming increasingly important to evaluate the effects of proposed waste control methodologies on the total environment. An inescapable byproduct of any separation process is the concentrated waste product and rarely is it possible to develop practical treatment methods for specific waste occurring in any of the three basic environmental areas without affecting at least one other area; thus, a program for the assessment of effects on water quality was included in the initial planning of the full-scale limestone injection project.

Ash Handling System

The Shawnee ash collection and disposal system is typical of many coal-fired thermal power plants. The ash is removed from the gas stream by mechanical separators and electrostatic precipitators in series and is then pumped to the ash disposal area. The water used to sluice collected ash to the disposal area is discharged to a receiving stream, the Ohio River, after the suspended solids have settled from it. During boiler injection of limestone, solid reaction products and unreacted lime is removed from the gas stream along with the fly ash. Unit 10 at Shawnee is equipped with mechanical cyclone separators in series with electrostatic precipitators. The combined system removes in excess of 98 percent of the fly ash; 66 percent in the mechanical units and approximately 95 percent of the remaining ash in the precipitators. (The collection efficiency of the system when limestone is utilized is discussed in appendix F.) The Shawnee units are equipped with V-type wet bottom hoppers for the collection of bottom ash and hoppers for collection of the pyrites which are rejected from the pulverizers. Ash from these hoppers and solids from dust collectors at various points in the coal-handling system are pumped to a settling pond. The clarified liquid effluent flows without treatment to the receiving stream, the Ohio River.

The Shawnee Steam Plant discharges an average of 20 million gallons per day from its ash disposal system. Sluicing from the mechanical collector hoppers accounts for approximately 30 percent of the flow and electrostatic precipitator sluicing represents approximately 22 percent. Of the remaining flow, bottom ash sluice is some 21 percent, pyrite sluice is about 17 percent, and the remaining 10 percent is derived from dust collectors, line cleaning, and miscellaneous flows. Since the portion of the injected limestone that is removed from the gas stream is collected by the mechanical and electrostatic collectors, only these require significant additional sluice flow.

Waste products from the limestone injection system affect the waste disposal system in three ways: (1) they increase the quantity of liquid effluent because additional flow is required to sluice the added volume of waste products; (2) they increase the amount of suspended solid waste and alter its settling characteristics; and (3) they alter the quality of the disposal pond water.

Evaluation Program

Objectives

The program for the evaluation of the effects of limestone injection on the plant ash disposal system, and subsequently on the environment, was designed to define the changes in overall quality of water being discharged from the system and to determine the increased quantity of sluice water required and the increased solids loading on the ash settling pond. Specifically the objectives of the evaluation program were:

1. To evaluate quantitatively the effects on water quality of the various limestone types injected.
2. To estimate the potential effects on the water quality of receiving streams from a multi-unit or large-scale limestone injection installation.
3. To determine the increase in quantity of water required to transport the increased solid wastes and to estimate the effect of the increased discharge on water quality of receiving streams.
4. To determine the increase of solid waste produced due to limestone injection and to estimate the effect of this increase on land use.
5. To evaluate the effects on the settling characteristics of ash contained in sluice water.

The water quality sampling portion of the program was designed specifically to provide the necessary data to (1) identify resulting water quality changes due to limestone injection, (2) determine, if possible, the correlation between input variables and resulting water quality alteration, and (3) determine the potential degradation of receiving streams.

Methodology

Table 1 outlines the sample parameters determined at the onset of the evaluation program, along with the methods and equipment used. Subsequent to the initial sampling, an emission spectrographic analysis was made of an ash sluice sample from a unit without limestone injection and one collected from unit 10 during injection. Table 2 lists the constituents identified in each analysis. The identification of the elements listed is positive; however, the quantitative measurements are only approximations. Analysis of several parameters was added to the program following review of the spectrographic results and these are shown in Table 3, together with a list of heavy metals and trace elements which were scheduled for periodic determination during the long-term test phase. Curtailment of that testing period limited the amount of trace element data obtained.

Since only unit 10 was utilized for limestone injection it was necessary to isolate, for sampling purposes, the sluicing operations of this unit from the other units of the plant. Also, it was necessary to determine the effect of limestone injection on each type of collector sluicing to provide a basis for projection of the data. Similar sampling was conducted on units other than 10 to provide baseline or background concentration for normal ash sluicing.

Table 1

Sample Program

Sample Parameter	Method	Equipment
Calcium	Specific Ion Electrode with EDTA Titration	Orion Meter No. 404 Electrode Model 92-20
Hardness	Specific Ion Electrode with EDTA Titration	Orion Meter No. 404 Electrode Model 92-32
Magnesium	EDTA Titration (Using a Magnesium Indicator) or by difference	Burette and Reagents
Dissolved Solids	Conductimetric	Dissolved Solids Meter
Suspended Solids	Gravimetric	Balance, Matched Filters, Oven
Sulfate	Turbidimetric	Turbidimeter
Sulfite	Titration with Sodium Thiosulfate (Starch Indicator)	Burette and Reagents
pH	Electrometric	pH Meter and Buffers
Alkalinity	Titration (.02N H_2SO_4)	pH Meter, Burette and Reagents
Conductance	Conductimetric	Conductivity Meter
Color	Visual Comparison using Platinum-Colbalt Standards	Matched Nessler Tubes
Chloride	Specific Ion Electrode Titration with Silver Nitrate	Orion Meter No. 404 Electrode Model 94-17
Iron	Atomic Absorption	Water Quality Laboratory Chattanooga
Manganese	Atomic Absorption	Water Quality Laboratory Chattanooga
Silica	Technicon Auto-Analyzer	Water Quality Laboratory Chattanooga

Table 2

Spectrographic Analysis of Ash Sluice Water

Element Found	Mechanical Collector, Unit 7 No Limestone	Mechanical Collector, Unit 10 Limestone Test 4A
Calcium	Major Constituent	Major Constituent
Iron	Major Constituent	Major Constituent
Aluminum	Major Constituent	Major Constituent
Silicon	Major Constituent	Major Constituent
Magnesium	Major Constituent	Major Constituent (-)*
Sodium	Major Constituent	Major Constituent (-)*
Potassium	Major Constituent	Major Constituent (-)*
Titanium	Major Constituent	Major Constituent (-)*
Manganese	Trace Constituent	Minor Constituent
Zinc	Minor Constituent	Minor Constituent
Tin	Trace Constituent	Trace Constituent
Copper	Trace Constituent	Trace Constituent
Silver	Trace Constituent	Trace Constituent
Strontium	Not Detected	Trace Constituent
Vanadium	Trace Constituent	Trace Constituent
Molybdenum	Not Detected	Trace Constituent
Gallium	Not Detected	Trace Constituent
Mercury	Not Detected	Trace Constituent**
Lead	Not Detected	Trace Constituent**
Boron	Trace Constituent	Trace Constituent
Nickel	Trace Constituent	Trace Constituent
Barium	Trace Constituent	-
Chromium	Trace Constituent	-
Phosphorus	Trace Constituent	-

*Less than other major components, but more than minor quantities.

**Quantity is at the lower limit of detection for emission spectrograph.

Table 3

Sample Program

Sample Parameter	Method	Equipment
Routine Analysis		
Sodium	Atomic Absorption	Water Quality Laboratory Chattanooga
Potassium	Atomic Absorption	Water Quality Laboratory Chattanooga
Aluminum	Colormetric - Aluminon	Water Quality Laboratory Chattanooga
Heavy Metals - Trace Elements		
Silver	Atomic Absorption	Water Quality Laboratory Chattanooga
Lead	Atomic Absorption	Water Quality Laboratory Chattanooga
Barium	Atomic Absorption	Water Quality Laboratory Chattanooga
Mercury	Acid Digestion - Flameless Atomic Absorption	Water Quality Laboratory Chattanooga
Copper	Atomic Absorption	Water Quality Laboratory Chattanooga
Arsenic	Colormetric SDDC (Standard Methods)	Water Quality Laboratory Chattanooga
Cadmium	Atomic Absorption	Water Quality Laboratory Chattanooga

Figure 1 shows a schematic diagram of the sampling locations. Most of the samples were collected from locations 1 and 1A. The required isolation of unit 10 necessitated sampling directly from the sluice pipe outlet rather than the pond and obtaining comparable background data made sampling from normal ash removal operations on other unit pipe outlets mandatory. Location 2 indicates the source of the ash pond discharge samples and location 3 shows the placement of the ash pond monitor for pH and conductivity. Mean values of all data collected from locations 1, 1A, and 2 have been tabulated and are presented throughout this report. Examples of the computer printout formats for the types of data stored are shown at the end of this appendix.

Waste Quantities

The increase in solid and liquid waste caused by the injection of limestone was determined from theoretical projections and plant sluice flow records. Although measurement of the nonfilterable or undissolved solids in the sluice flow gives an indirect measurement of the added solid waste produced, it seemed desirable to use theoretical factors since (1) the lowered efficiency of the electrostatic precipitator during limestone injection lowers the solid waste collected and thus the measurable quantity in the sluice flow, and (2) sluicing operations produce a pulsing, nonuniform flow of highly variable solids content.

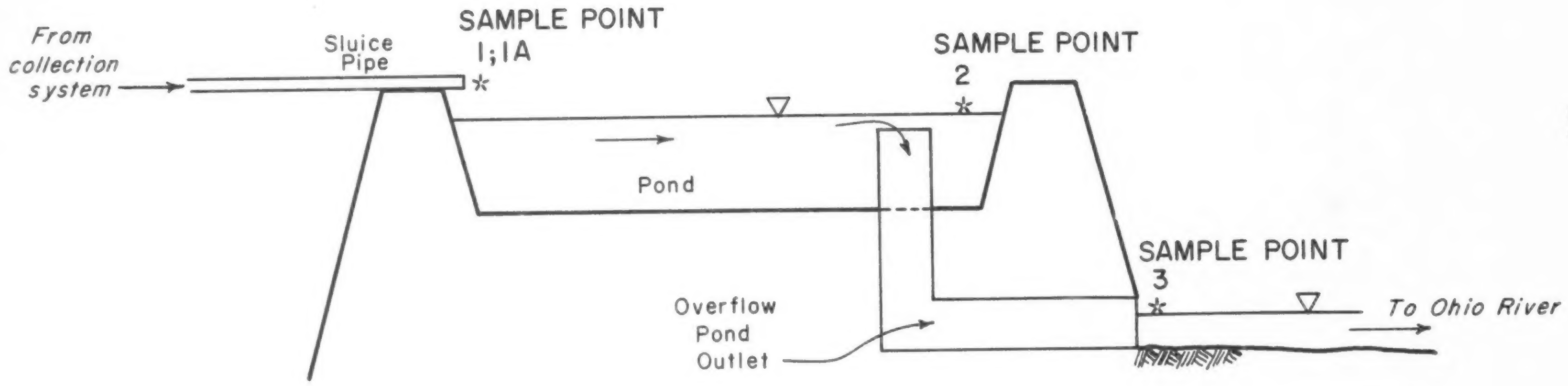
Figure 2 shows the theoretical increase in solid waste produced as a function of stoichiometric limestone injected for the assumed SO_2 removal efficiencies. This figure also shows the theoretical increase in sluice flow required assuming the same concentration of solids in the ash-limestone sluice as in the ash sluice.

The actual ash burden and sluice flows shown on figure 2 were projected to a stoichiometry of 1 and a 20 percent SO_2 removal from actual test conditions. The ash burden is less than the theoretical because of factors already discussed. The sluice flow is affected by these factors also; however, the flow is further lessened by the increased concentration of solids in the ash-limestone sluice from the electrostatic precipitators during limestone injection. The average solids in the sluice water during normal operations is about 1.2 percent. Sluice flow from the mechanical and electrostatic precipitators contains more solids than the discharge from the other sources, averaging about 1.5 percent. Similar sampling of the sluice water from unit 10 shows that significantly more solids are suspended in the water from the electrostatic precipitator hoppers during limestone injection tests than during normal operation. The average solids content is 2.5 percent, an increase of 67 percent. The solids content of the mechanical collector sluice water shows no such increase. Because of the higher density, less than the calculated flow is sufficient for limestone injection. It is assumed that addition of limestone products allows the ash-mix to flow from the hoppers more easily; however, this was not further investigated.

Theoretical increases in sluice flow were used to project water quality data to full-scale conditions. Figure 2 shows that for the Shawnee plant this is not greatly different from actual conditions. The quantity of water discharged from the ash sluice system of

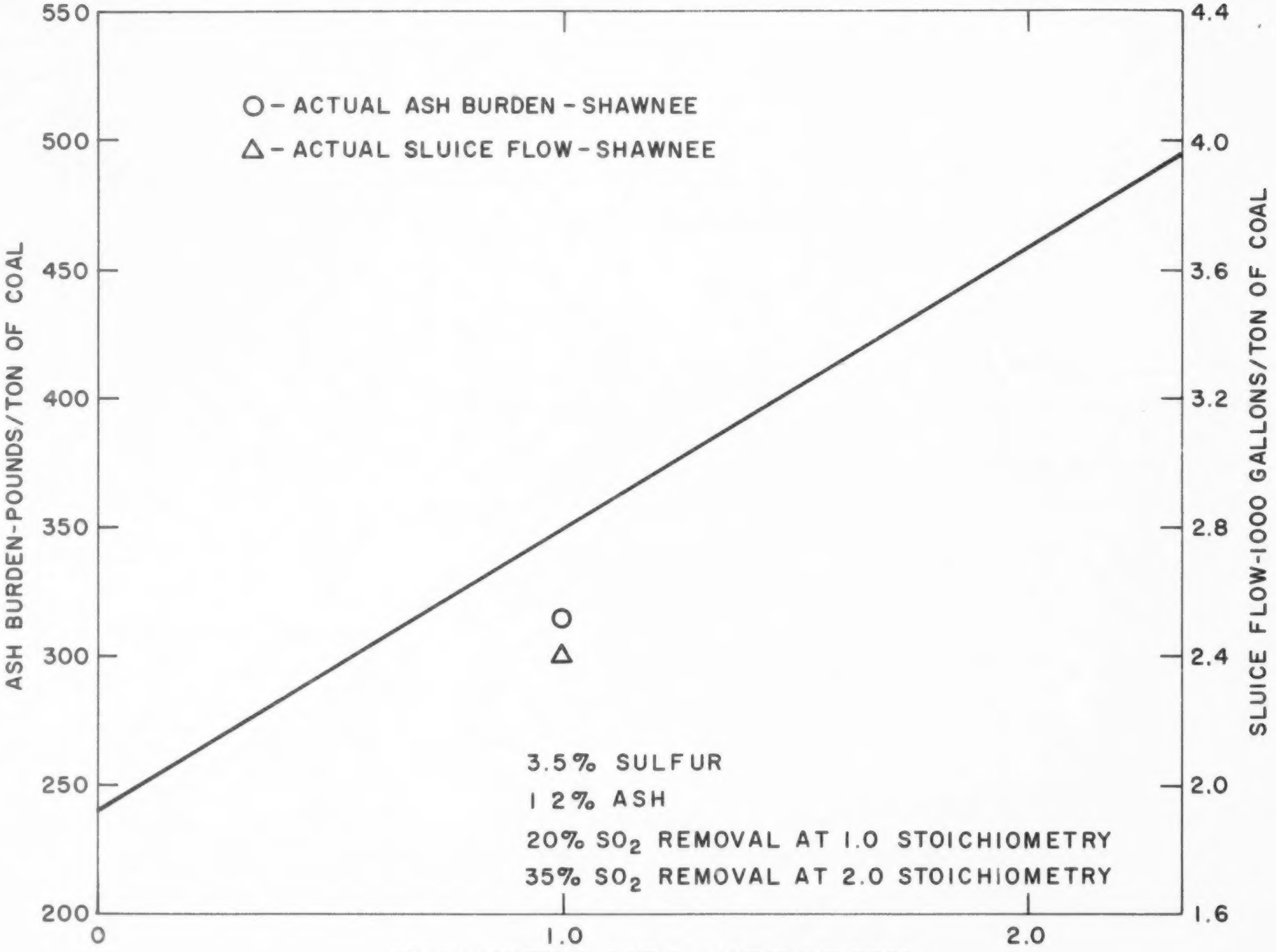
Figure 1

WATER QUALITY SAMPLING LOCATIONS



SAMPLE POINT 1 - Unit 10 Pipe Outlet - Limestone Injection

SAMPLE POINT 1A - Units 1-9 Pipe Outlets - No Injection, Background Only



THEORETICAL TOTAL ASH BURDEN AND SLUICE FLOW
LIMESTONE INJECTION

Figure 2

coal-fired electric power generating plants is dependent on the type of fuel-feed system, the percent ash in the coal, the type of ash collection system, the efficiency of the collection system, the type of pumping system and quantity of coal burned. The following data tabulation is taken from a review of typical plants of the pulverized fuel type:

Ash Collector System	Efficiency of System	Percent Ash in Coal	Average Flow Gals./Ton Coal
Mechanical	60-68	11-14	1400-1600
Electrostatic Precipitators	90-98	11-14	1500-1900
Mechanical-Electrostatic	96-98	11-14	1500-2200

Much of these data are based on flows obtained from pump records and may vary from the actual flow by as much as 20 percent, but do indicate the approximate magnitude of sluice water discharged. The Shawnee Steam Plant discharges an average sluice flow of about 1,600 gallons per ton of coal burned.

Results

Background Water Quality

Sampling of ash sluice for the development of background or baseline information on units generating with no limestone injection resulted in obtaining 104 separate samples on which over 1,500 determinations were made. Table 4 lists the concentrations of various parameters for each type of sluice. While individual samples exhibit some variation within the types of sluice, the variation from type to type is much greater.

A composite mixture of presumed conservative chemical parameters, based on weighted flows, should represent the pond effluent quality with respect to these parameters. (Table 5 shows the Ohio River intake water quality analysis used in this determination.) With the exception of calcium, hardness, and dissolved solids, all interrelated parameters, the computed composite values are not significantly different from the values obtained from analysis of pond effluent samples (figure 1, location 2) shown in table 6. The actual differences are essentially all due to the variation in calcium concentrations. The calcium concentrations from the sluice pipes were from 15 to 25 percent higher than concentrations at the pond outlet, indicating a loss of calcium from precipitation, adsorption or other mechanisms. Table 6 also includes some concentration data for parameters not included in table 4. These determinations were not made on individual sluice types except during limestone injection.

A continuous conductivity recorder, Delta Scientific Model 3314, and a recording battery-operated pH meter, Photovolt Aquacord Model 130, were used to monitor the ash pond effluent for 28 days (figure 1, location 3). The mean three-hour pH was 11.5 and values ranged from 11.2 to 12.4. The three-hour mean conductivity was 1200 M mhos and the range was 900 to 1700. The values were within ± .2 pH units and ± 10 percent of the conductivity of instantaneous grab sample values.

Table 4

Sluice Water Quality

Base Test (Baseline Data)
(No Limestone Injection)

Parameter	Mean Concentration			
	Type 1	Type 2	Type 3	Type 4
pH Su	9.9	11.3	10.0	8.5
Phen Alk $CaCO_3$ mg/l	102	525	83	26
T Alk $CaCO_3$ mg/l	156	574	134	74
Residue Total mg/l	14072	13665	5054	853
Residue Tot Flt mg/l	603	2004	468	208
Tot Hard $CaCO_3$ mg/l	310	657	309	176
Calcium Ca mg/l	202.3	424.3	239.0	131.5
Mgnsium Mg mg/l	101.7	233.1	70.0	44.7
Chloride Cl mg/l	10	9	8	7
Cnductvy At$_{25}$C micromho	844	2404	680	245
Silica SiO_2 mg/l	7.2	7.9	8.1	5.9
Sodium Na mg/l	32.00	17.88		
Ptssium K mg/l	17.54	11.00		
Mangnese Mn ug/l	1223	2454	1313	20
Iron Total ug/l	48035	42678	23666	600
Iron Ferrous ug/l	310			
Zinc Zn ug/l	2572	762		
Aluminum Al ug/l	1411	1308		
Color PT-CO Units	6	5	7	20
Turb JKSN JU	106	71	70	50
Sulfate SO_4 mg/l	247	177	130	43
Sulfite SO_3 mg/l	2.30	2.20	1.25	.78

Type 1 - Electrostatic Precipitators

Type 2 - Mechanical Collectors

Type 3 - Bottom Ash

Type 4 - Pyrite

Table 5

Intake Water Quality

Shawnee Steam Plant

Ohio River Mile 945.5

Parameter	Conc Mg/1
Dissolved Oxygen	6.0
pH	8.0
Alkalinity (Pheno)	0
Alkalinity (Total)	59.0
Hardness ($CaCO_3$)	59.0
Calcium	17.0
Magnesium	4.0
Iron (Total)	1.1
Dissolved Solids	180.0
Total Solids	230.0
Sulfate	15.0
Conductance (M Mohs)	160.0

Table 6

Baseline Concentration

Ash Pond Overflow

Parameter	Mean
pH Su	11.2
Phen Alk $CaCO_3$ mg/l	188
T Alk $CaCO_3$ mg/l	218
Residue Total mg/l	869
Residue Tot Flt mg/l	798
Tot Hard $CaCO_3$ mg/l	375
Calcium $CaCO_3$ mg/l	246.1
Mgnsium $CaCO_3$ mg/l	136.6
Chloride Cl mg/l	11
Conductivy $At_{25}C$ micromho	1085
Silica SiO_2 mg/l	6.4
Sodium Na mg/l	13.00
Ptssium K mg/l	6.12
Mangnese Mn ug/l	10
Iron Total ug/l	188
Copper Cu ug/l	21
Zinc Zn ug/l	176
Silver Ag ug/l	10<
Barium Ba ug/l	262
Aluminum Al ug/l	1184
Color PT-CO Units	5
Turb JKSN JU	6
Sulfate SO_4 mg/l	133
Sulfite SO_3 mg/l	2.03
Nitrate NO_3 mg/l	.05
Phosphate PO_4 mg/l	.40
Mercury Hg ug/l	.5<
Cadmium Cd ug/l	10<
Lead Pb ug/l	100<
Titanium Ti ug/l	1<
Chromium Cr ug/l	50<
Arsenic As ug/l	60

Since the composite of individual sluice types was reasonably representative of the pond effluent, the individual types with limestone injection could be compared to the corresponding type without injection. The actual effect of limestone injection was thus determined by type. For projection of limestone effect on full-scale installations, a composite was used.

Although the hardness concentration and total dissolved solids (total filterable residue) of the normal ash pond discharge exceed generally desirable water quality concentration even prior to limestone injection, only the pH exceeds generally established effluent guidelines. The pH of this discharge will, however, meet stream standards since the Ohio River provides ample dilution to reduce the pH to acceptable limits beyond a very short mixing zone. Thus, prior to the limestone injection, the ash sluice discharge is, with the exception of pH, acceptable for release to the river under regulations presently existing in most areas of the country.

Water Quality; Limestone Injection

Sampling Program

During limestone injection 105 samples of ash-limestone sluice water were collected from location 1 (figure 1) and over 2,100 individual analyses were made. This sampling of each type of sluicing operaton, electrostatic, mechanical, bottom ash, and pyrite, was grouped according to test phase. The data designated Actual Test were collected during Phase I and II of the test program, Prec. Test during the precipitator testing, and the Aragonite, Marl, and Long-Term designations are self-explanatory. The separation of the precipitator test phase from the initial test phases is a matter of record keeping and the separation of data has no analytical significance. Tables 7, 8, 9, and 10 show the mean concentration values for each sample phase.

Data Analyses

In analyzing resulting concentration data, an attempt was made to correlate certain parameter concentrations with test input variables that obviously should affect the water quality to some degree. However, since the test program had demonstrated that variation of controlled and uncontrolled process variables were difficult to correlate with test results and since the sluice water quality is affected by other factors such as constituent solubilities, influent water quality, unreacted products and sluice flow density, meaningful correlations were not greatly expected. Figures 3, 4, and 5 are computer printouts of linear correlation analysis of limestone feedrate vs soluble calcium, limestone feedrate vs total dissolved solids, stoichiometry vs soluble sulfate, respectively. These examples indicate that no significant correlation exists, or more meaningful, that no significant correlation can be determined. Brief attempts at correlation by nonlinear and multivariate analysis proved equally nonproductive, and correlation analysis was not further investigated.

The lack of input-output correlation does not, however, negate the value of the data for determination of the general level of water quality effects from limestone injection or

Table 7

Sluice Water Quality

Limestone Injection (Actual Test)

Parameter	Mean Concentration			
	Type 1	Type 2	Type 3	Type 4
pH Su	12.2	12.4	11.2	9.2
Phen Alk $CaCO_3$ mg/l	2179	2360	534	23
T Alk $CaCO_3$ mg/l	2338	2486	597	84
Residue Total mg/l	35233	23777	4136	728
Residue Tot Flt mg/l	11460	12116	1991	188
Tot Hard $CaCO_3$ mg/l	2362	2566	793	213
Calcium Ca mg/l	1179.3	1311.1	408.8	163.3
Mgnsium Mg mg/l	1187.3	1261.1	382.7	50.0
Chloride Cl mg/l	63	40	10	9
Cnductvy At$_{25}$C micromho	14073	15677	2545	310
Silica SiO_2 mg/l	2.7	2.0	5.7	3.5
Sodium Na mg/l	57.16	36.66	14.66	
Ptssium K mg/l	96.66	55.50	6.80	
Mangnese Mn ug/l	97	81	362	
Iron Total ug/l	5577	3045	12581	
Zinc Zn ug/l	835	218	274	
Color PT-CO Units	5	5	6	12
Turb JKSN JU	116	120	84	70
Sulfate SO_4 mg/l	472	288	165	48
Sulfite SO_3 mg/l	15.78	12.27	5.88	5.83
Aluminum Al ug/l	5000	1180	132	
Limestone Type BCR No.	2061	2061	2061	2061
Average Stoichio	2.09	2.04	2.00	2.99
SO_2 Fly Ash Bioloutl % By Wt.	4.02	4.02	4.04	3.22
SO_2 in Bot Ash % By Wt.	2.35	2.55	2.41	.50
Limestone Feedrate lb/lb Coal	.14	.14	.14	.15

Type 1 - Electrostatic Precipitators

Type 2 - Mechanical Collectors

Type 3 - Bottom Ash

Type 4 - Pyrite

Table 8

Sluice Water Quality

Limestone Injection (Precipitator Test)

Parameter	Mean Concentration		
	Type 1	Type 2	Type 3
pH Su	11.4	11.9	11.1
Phen Alk $CaCO_3$ mg/l	875	2150	379
T Alk $CaCO_3$ mg/l	1003	2266	450
Residue Total mg/l	22666	19333	3448
Residue Tot Flt mg/l	3683	9450	1433
Tot Hard $CaCO_3$ mg/l	1093	1733	735
Calcium Ca mg/l	866.6	883.3	558.3
Mgnsium Mg mg/l	226.6	850.0	176.6
Chloride Cl mg/l	15	21	12
Cnductvy At$_{25}$C micromho	5033	12700	2223
Silica SiO_2 mg/l	6.7	1.3	4.6
Color PT-CO Units	7	5	6
Turb JKSN JU	101	93	75
Sulfate SO_4 mg/l	453	253	178
Sulfite SO_3 mg/l	3.83	8.00	7.50
Limestone Type BCR No.	2061	2061	2061
Average Stoichio	1.67	1.67	1.67
SO_2 Fly Ash Boil Outl % By Wt.	3.61	3.61	3.61
SO_2 in Bot Ash % By Wt.	.50	.50	.50
Limestone Feedrate lb/lb Coal	.12	.12	.12

Type 1 - Electrostatic Precipitators

Type 2 - Mechanical Collectors

Type 3 - Bottom Ash

Table 9

Sluice Water Quality

Limestone Injection
(Aragonite and Mich Marl)

	Mean Concentration			
	Aragonite		Mich Marl	
Parameter	Type 1	Type 2	Type 1	Type 2
pH Su	11.3	12.4	12.2	12.0
Phen Alk $CaCO_3$ mg/l	238	2348	1933	1773
T Alk $CaCO_3$ mg/l	298	2436	2020	1823
Residue Total mg/l	16940	21360	40000	25000
Residue Tot Flt mg/l	1220	9840	9600	9033
Tot Hard $CaCO_3$ mg/l	940	3020	1800	3300
Calcium Ca mg/l	750.0	2600.0	800.0	2425.0
Mgnsium Mg mg/l	190.0		1000.0	875.0
Chloride Cl mg/l	26	17	45	14
Cnductvy At$_{25}$C micromho	1430	10740	10866	10513
Silica SiO_2 mg/l	10.6	5.4	16.5	2.5
Sodium Na mg/l	37.80	15.84	58.00	15.50
Ptssium K mg/l	15.70	19.00	87.00	24.00
Mangnese Mn ug/l	1440	336	520	4140
Iron Total ug/l	132600	19396	3200	7550
Zinc Zn ug/l	5960	662	1630	1470
Aluminum Al ug/l	1660	1240		
Color PT-CO Units	7	6	8	8
Turb JKSN JU	140	125	116	108
Sulfate SO_4 mg/l	382	272	470	333
Sulfite SO_3 mg/l	5.60	13.20	9.00	5.83
Limestone Type BCR No.	1683	1683	2129	2129
Average Stoichio	2.97	2.97	2.16	2.16
SO_2 Fly Ash Boil Outl % By Wt.	3.12	3.12	3.74	3.74
SO_2 in Bot Ash % By Wt.	.24	.24	.40	.40
Limestone Feedrate lb/lb Coal				

Type 1 - Electrostatic Precipitators
Type 2 - Mechanical Collectors

Table 10

Sluice Water Quality

Limestone Injection (Long-Term)

Parameter	Mean Concentration	
	Type 1	Type 2
pH Su	12.4	12.3
Phen Alk $CaCO_3$ mg/l	2300	1938
T Alk $CaCO_3$ mg/l	2414	2023
Residue Total mg/l	17571	17190
Residue Tot Flt mg/l	11142	8754
Tot Hard $CaCO_3$ mg/l	4085	3072
Calcium $CaCO_3$ mg/l	3442.8	2677.2
Mgnsium $CaCO_3$ mg/l	642.8	395.4
Chloride Cl mg/l	9	16
Cnductvy $At_{25}C$ micromho	12685	10827
Silica SiO_2 mg/l	1.9	2.0
Sodium Na mg/l	15.57	10.44
Ptssium K mg/l	42.00	14.83
Mangnese Mn ug/l	2542	3145
Iron Total ug/l	142000	70777
Copper Cu ug/l	512	245
Zinc Zn ug/l	4771	1775
Silver Ag ug/l	50	65
Barium Ba ug/l	3500	3000
Color PT-CO Units	9	5
Chromium Cr ug/l	680	725
Turb JKSN JU	157	93
Sulfate SO_4 mg/l	885	492
Sulfite SO_3 mg/l	10.14	7.27
Mercury Hg ug/l	3.7	.4
Nitrite NO_2-N mg/l	.01	.01
Nitrate NO_3-N mg/l	.41	.54
Arsenic As ug/l	90	83
Cadmium Cd ug/l	140	110
Lead Pb ug/l	590	400
Aluminum Al ug/l	3433	1116
Titanium Ti ug/l	27	13

Type 1 - Electrostatic Precipitators

Type 2 - Mechanical Collectors

LIMESTONE INJECTION

ELECTROSTATIC PRECIPITATOR DISCHARGE

X = Limestone Feedrate (Lbs/lbs Coal)

Y = Calcium as $CaCO_3/10$

VARIABLE	MEAN	VARIANCE	STD DEVIATION
X	0.144667	8.40952E-4	2.89992E-2
Y	117.933	5178.92	71.9647

SOURCE OF VARIATION	D. F.	SUM OF SQUARES	MEAN SQUARE
TOTAL	14	72504.9	5178.92
REGRESSION	1	1824.47	1824.47
ERROR	13	70680.5	5436.96

INDEX OF DETERMINATION	2.51634E-2
CORRELATION COEFFICIENT	0.15863
F-RATIO TEST STATISTIC	0.335568

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	60.9842	-155.855	277.824
B	393.658	-1077.89	1865.21

X-ACTUAL	Y-ACTUAL	Y-CALC	95 PCT PREDICTION LIMITS	
0.15	33	120.033	-45.0609	285.127
0.14	54	116.096	-48.9537	281.146
0.18	260	131.843	-41.0672	304.752
0.18	120	131.843	-41.0672	304.752
0.17	32	127.906	-41.1623	296.974
0.13	120	112.16	-54.1537	278.473
0.15	90	120.033	-45.0609	285.127
0.15	90	120.033	-45.0609	285.127
0.17	40	127.906	-41.1623	296.974
0.07	90	88.5402	-109.619	286.699
0.1	70	100.35	-77.1738	277.874
0.14	200	116.096	-48.9537	281.146
0.14	200	116.096	-48.9537	281.146
0.15	170	120.033	-45.0609	285.127
0.15	200	120.033	-45.0609	285.127

Figure 3

LIMESTONE INJECTION

ELECTROSTATIC PRECIPITATOR DISCHARGE

```
X = Limestone Feedrate (Lbs/lbs Coal)

Y = Total Dissolved Solids

VARIABLE        MEAN            VARIANCE          STD DEVIATION
   X             0.144667        8.40952E-4         2.89992E-2
   Y             35233.3         1.87531E+8         13694.2

SOURCE OF       D. F.           SUM OF             MEAN
VARIATION                       SQUARES           SQUARE
TOTAL            14              2.62543E+9         1.87531E+8
REGRESSION       1               5.68303E+6         5.68303E+6
ERROR            13              2.61975E+9         2.01519E+8

INDEX OF DETERMINATION           2.1646E-3
CORRELATION COEFFICIENT          4.65253E-2
F-RATIO TEST STATISTIC           2.82009E-2

PARAMETER       VALUE           95 PCT CONFIDENCE LIMITS
   A            32054.9         -9691.43            73801.3
   B            21970.5         -261335.            305276.

X-ACTUAL       Y-ACTUAL         Y-CALC            95 PCT PREDICTION LIMITS

  0.15          14000            35350.5            3566.35         67134.7
  0.14          26000            35130.8            3355.06         66906.5
  0.18          36000            36009.6            2720.7          69298.6
  0.18          48000            36009.6            2720.7          69298.6
  0.17          64000            35789.9            3240.57         68339.3
  0.13          40000            34911.1            2892.12         66930.1
  0.15          33000            35350.5            3566.35         67134.7
  0.15          19000            35350.5            3566.35         67134.7
  0.17          20000            35789.9            3240.57         68339.3
  0.07          38500            33592.9           -4557.1          71742.8
  0.1           39000            34252.             74.7705         68429.2
  0.14          39000            35130.8            3355.06         66906.5
  0.14          28000            35130.8            3355.06         66906.5
  0.15          56000            35350.5            3566.35         67134.7
  0.15          28000            35350.5            3566.35         67134.7
```

Figure 4

LIMESTONE INJECTION

ELECTROSTATIC PRECIPITATOR DISCHARGE

X = Stoichiometry

Y = Sulfate (as SO_4)

VARIABLE	MEAN	VARIANCE	STD DEVIATION
X	2.19867	0.924884	0.961709
Y	472	27517.1	165.883

SOURCE OF VARIATION	D. F.	SUM OF SQUARES	MEAN SQUARE
TOTAL	14	385240	27517.1
REGRESSION	1	64975.7	64975.7
ERROR	13	320264.	24635.7

INDEX OF DETERMINATION	0.168663
CORRELATION COEFFICIENT	0.410686
F-RATIO TEST STATISTIC	2.63746

PARAMETER	VALUE	95 PCT CONFIDENCE LIMITS	
A	316.25	90.7959	541.705
B	70.8382	-23.6161	165.293

X-ACTUAL	Y-ACTUAL	Y-CALC	95 PCT PREDICTION LIMITS	
1.58	270	428.175	72.3144	784.035
1.68	360	435.259	80.8268	789.69
3.91	410	593.228	206.769	979.686
3.91	620	593.228	206.769	979.686
4.02	860	601.02	210.102	991.938
2.18	380	470.678	119.644	821.712
1.87	390	448.718	96.3181	801.118
1.87	400	448.718	96.3181	801.118
2.43	380	488.387	136.678	840.096
1.03	500	389.214	21.2371	757.19
1.88	540	449.426	97.1085	801.744
1.43	750	417.549	59.0896	776.008
1.43	350	417.549	59.0896	776.008
1.88	550	449.426	97.1085	801.744
1.88	320	449.426	97.1085	801.744

Figure 5

for the projection of these effects to full-scale installations for problem definition. Figures 6 and 7 are examples of the distribution with a single population mean. The assumption of a single population mean is, of course, not valid; however, the data fit was sufficient to allow the use of mean values for definition and projection of effects. (Refer to the corresponding example data printout sheets at the end of this appendix for the range of input values covered by this group analysis.)

Injection Effects

Results of the extensive water quality determinations indicate that the most significant major quantity parameters affected are pH, dissolved solids concentration and hardness. In addition, the sulfate and magnesium concentrations and alkalinity are greatly increased. Table 11 shows the increase in concentrations of each of these parameters. The total effect is even greater, however, since the total quantity of aqueous waste from these sluice operations is also increased by the increased flow. The total soluble calcium concentration is somewhat higher than anticipated as is the total soluble magnesium, which is quite soluble as $MgSO_4$.

The pH of the sluice is elevated slightly; however, it is highly buffered in the range above 10 due to the added calcium. The most significant effect of this added alkalinity is to require much more dilution in the stream for neutralization or to require large quantities of additional acid if treatment is utilized. Figure 8 shows the acid required for neutralization of the sluice with and without limestone injection.

Comparison of the sluice data obtained during the long-term phase with that obtained during short-term runs indicates that the calcium and hardness concentrations were somewhat increased in the long-term run. (See tables 7 and 10.) The long-term data also fluctuated less widely. The average feedrates and stoichiometry were similar during each run and the same limestone type was used. The resulting higher concentration may be due to more stable sluicing operations when limestone is used fully during all hours of the day; however, this cannot be fully substantiated since insufficient data were obtained during the long-term phase. All projections are based on the earlier test data.

Comparison of the sluice water during injection of the Fredonia Valley stone, BCR 2061, with sluice during Aragonite, BCR 1683, and Michigan Marl, BCR 2129, indicates that there are not significant differences in quality. Both aragonite and marl sluice are somewhat higher in soluble magnesium, sodium, and potassium and lower in calcium than the Fredonia stone. The calcium and dissolved solids data from the electrostatic precipitators during aragonite testing appears extremely low and since the mechanical collector sluice shows no such unusual variation, the validity of the precipitator data as a representative sample is questionable.

Projection of the sluice data to full-scale utilization at Shawnee at low Ohio River flows indicates that no present stream standards should be exceeded. Projections are based on a composite analysis of the concentrations (indicated as actual test) weighted by theoretical flows for each type of sluice. A river flow of 48,100 cubic feet per second (cfs)

STATISTICAL DISTRIBUTION

Actual Test
Electrostatic Precipitators
Residue - Tot Flt

```
MANDSD
VERSION  11/02/70
ARITHMETIC MEAN, VARIANCE, AND STANDARD DEVIATION

INDIVIDUAL SET NUMBER 1
SAMPLE VALUES:
  2200  4900  8800  13000  18000  10000  13000  4000  7600
  14800  7600  18000  14000  24000  12000

MAXIMUM LIKELIHOOD ESTIMATES OF POPULATION PARAMETERS

     NUMBER OF VALUES =  15
      ARITHMETIC MEAN =  11460
   STANDARD DEVIATION =  5708.92
      SAMPLE VARIANCE =  3.25917E+7

UNBIASED ESTIMATES OF POPULATION PARAMETERS

      ARITHMETIC MEAN =  11460
   STANDARD DEVIATION =  5909.29
             VARIANCE = 3.49197E+7
```

Figure 6

STATISTICAL DISTRIBUTION

Actual Test
Mechanical Collectors
Calcium · $CACO_3$ (mg/l · 10^2)

```
MANDSD
VERSION  11/02/70
ARITHMETIC MEAN, VARIANCE, AND STANDARD DEVIATION

INDIVIDUAL SET NUMBER 1
SAMPLE VALUES:
  14  16  2.4  22  12  18  9.2  8.4  11  10  10  4  7
  16  14  16  20  26

MAXIMUM LIKELIHOOD ESTIMATES OF POPULATION PARAMETERS

     NUMBER OF VALUES =  18
      ARITHMETIC MEAN =  13.1111
   STANDARD DEVIATION =  5.96628
      SAMPLE VARIANCE =  35.5965

UNBIASED ESTIMATES OF POPULATION PARAMETERS

      ARITHMETIC MEAN =  13.1111
   STANDARD DEVIATION =  6.13926
             VARIANCE =  37.6905
```

Figure 7

Table 11

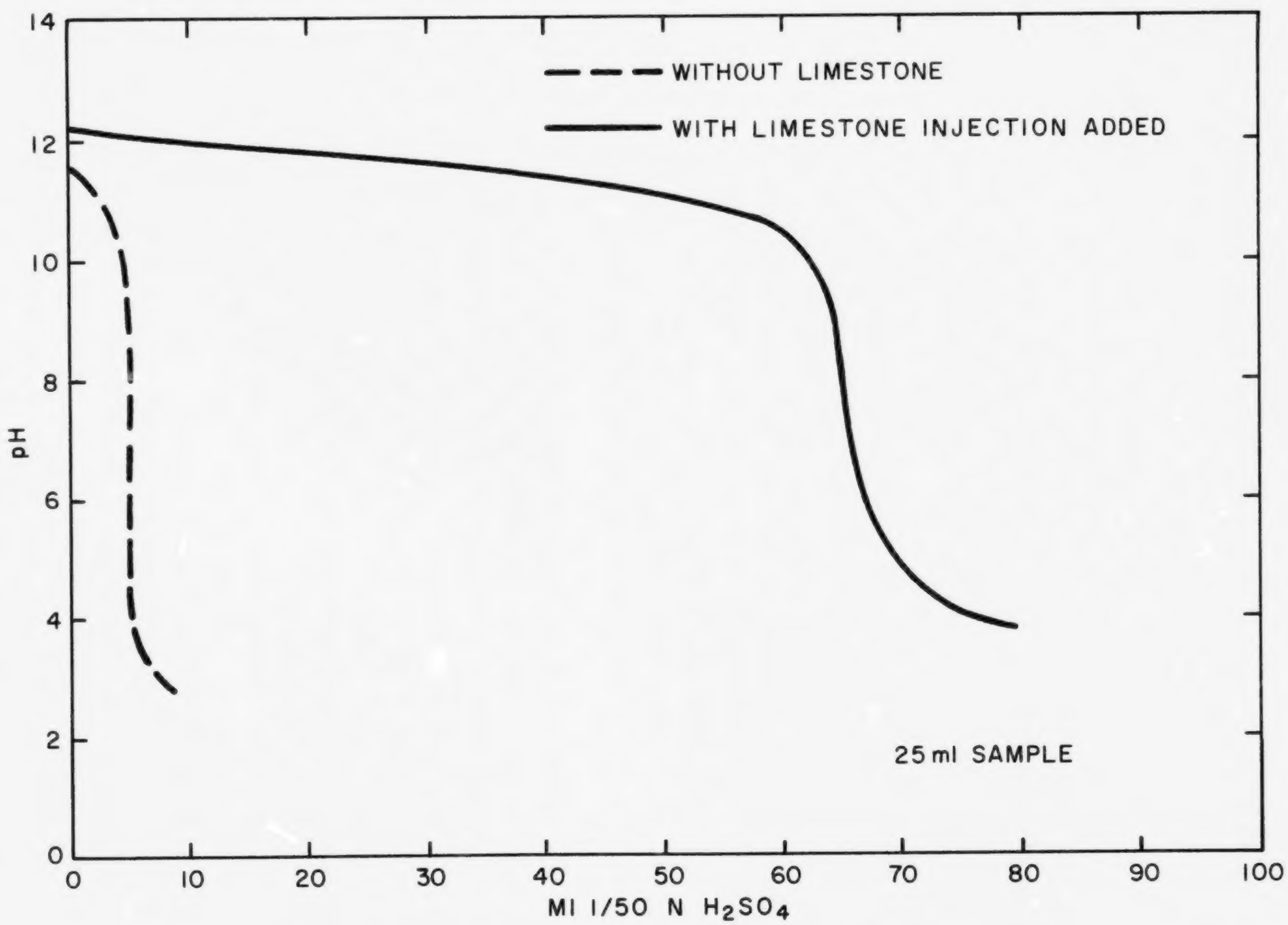
Sluice Water Quality

Limestone Injection

Type of Sluice	Parameter	Mean Concentration (mg/l)	% of Mean Concentration of Normal Operation
Mechanical	Ca	1311*	310
Mechanical	Mg	1261*	540
Mechanical	Hardness	2560*	390
Mechanical	pH	12.4**	Not applicable
Mechanical	Total Alkalinity	2486	430
Mechanical	SO_4	288	165
Mechanical	Total Dissolved Solids	12,116	600
Electrostatic	Ca	1179*	585
Electrostatic	Mg	1187*	1180
Electrostatic	Hardness	2362*'	760
Electrostatic	pH	12.4**	Not applicable
Electrostatic	Total Alkalinity	2338	1500
Electrostatic	SO_4	472	190
Electrostatic	Total Dissolved Solids	11,460	1900

* As $CaCO_3$

** Median Value; Units



ACID TITRATION-MECHANICAL COLLECTOR SLUICE

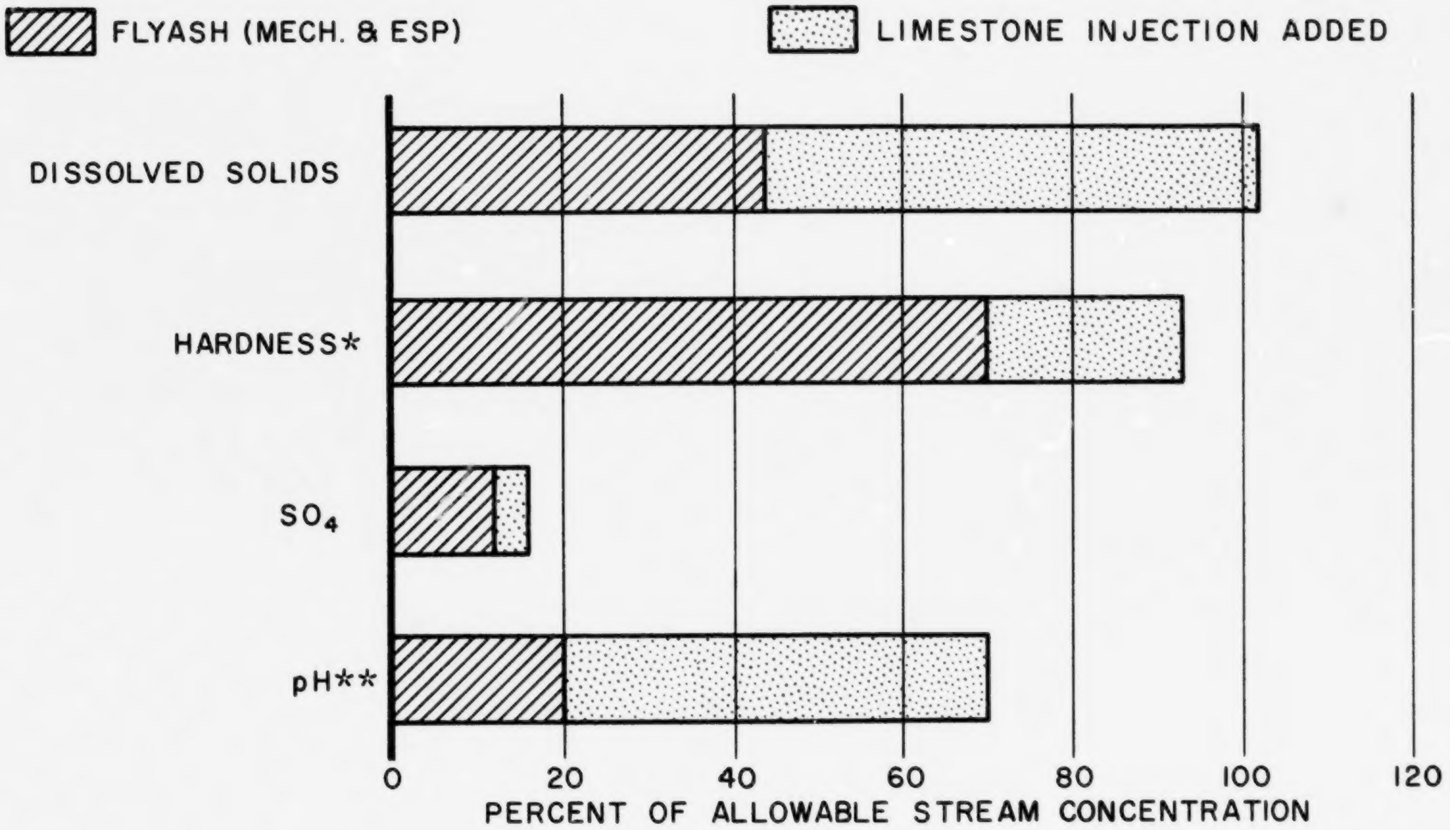
Figure 8

was used as is required for maximum concentration analysis by the Ohio River Valley Water Sanitation Commission for this portion of the Ohio River. The allowable concentrations are based on the following maximum in the stream: dissolved solids, 500 mg/l; sulfates, 150 hardness, 25 percent rise up to 150 mg/l; pH 9.0. These represent no particular set of standards but are levels often recommended or used by regulatory agencies as limits or guidelines. The most significant factor in this evaluation, however, is the very large flow of water past the Shawnee plant, even at critically low flows. The ratio of critical stream flow level, in cubic feet per second, to plant output, in megawatts, for Shawnee is 27.5. This is an extremely high ratio. In a survey of some 25 coal-fired steam plants the ratio ranged from 0.3 to 27.5; the maximum being the Shawnee plant. Critical flow levels used were the seven-day duration minimun flow occurring once in 10 years. Other flow levels are often used such as 1 day-20 year and 1 day-10 year minimum. Figure 9 shows the percent of allowable concentration in the stream if a full-scale limestone projection process were operated at a plant with a ratio of 1.0.

Figure 9 represents a projection of Shawnee data to an actual plant; and the plant size, river flow, and raw water analysis used in the projection are actual. The hypothetical water quality criteria discussed above was the basis for the maximum limits. The projection shows that the dissolved solids exceed the limits. The hardness value shown is actual concentration and the rise exceeds the recommended 25 percent. Although this hardness increase would not represent a significant water quality degradation by itself, it uses such a large percent of the residual dilution capacity of the stream as to be undesirable. The pH requires such a large portion of the total flow that a significant mixing zone would likely result.

The use of effluent standards to supplement stream standards is becoming more and more prevalent. EPA and many states have issued guidelines for effluent standards, some of which apply to all industries and others only to specific industries. Generally, the effluent standards place limits on constituents of organic origin trace metals or toxic materials, and pH. As of the date of this report, EPA has not issued its guidelines for the power industry. Table 12 lists the Ohio River Valley Water Sanitation Commission (ORSANCO) effluent standards for the Ohio River and effluent guidelines proposed by the state of Tennessee. Each of these standards cover all industrial discharges.

Only a very limited number of trace element and heavy metals analyses were made due to the curtailment of the long-term phase and in most cases only four sets of data are available. However, these data are sufficient to indicate the probable areas of concern. When limestone is utilized, concentrations of zinc, silver and lead exceed the limits of one or both of the standards specified in table 12. Barium, cadmium, copper, and manganese approach the limits indicated. All of these constituent concentrations are greatly increased by the limestone injection. Iron (total) is indicated as exceeding standards; however, much of this is lost in the pond and it is doubtful if limits will be exceeded. In general, the concentration of iron in the sluice is less during limestone injection than when no limestone is used.



*ACTUAL CONCENTRATION (mg/l)

**PERCENT OF AVAILABLE DILUTION REQUIRED

WATER QUALITY OF RECEIVING STREAM
AT CRITICAL PLANT LOAD AND STREAMFLOWS

Figure 9

Table 12

Effluent Standards

Parameter	ORSANCO Std. (Max. Limit)	State of Tennessee Effluent Guidelines (Daily Average) mg/l
Aluminum	--	250
Antimony	--	1.0
Arsenic	0.05	1.0
Barium	1.0	5.0
Cadmium	0.01	0.01
Chromium (Total)	0.05*	3.0
Copper	--	1.0
Cyanide	0.20	0.03
Iron (Total)	--	10.0
Lead	.05	0.1
Manganese	--	10.0
Mercury	.005	.005
Nichel	--	3.0
pH*	5.0-9.0	6.0-9.0
Selenium	--	0.01
Silver	0.05	0.05
Sulfate	--	1400
Zinc	--	2.0

* Hexavalent

ORSANCO includes a limit of 1,400 mg/l sulfates as an effluent maximum. The concentration during limestone injection only approaches this limit; however, a higher SO_2 removal percentage may cause the limit to be exceeded.

Investigation of water quality during wet limestone pilot plant operations showed that selenium may be found in the ash and the limestone sluice. A single analysis of sluice water from the dry injection process indicated selenium of 0.02 mg/l in the ash sluice and 0.04 in the limestone sluice. Both of these exceed recommended standards.

The analysis of soluble heavy metals and toxic elements in the aqueous waste stream from any proposed limestone injection process could likely be the major factor, together with pH, in determining the suitability of discharging the waste to receiving streams without treatment. Since treatment of various metals in such large quantities of water is not generally economically feasible, closed-cycle operation would likely be required.

The estimated costs for converting an existing ash pond, with discharge to the river, to a limestone-ash pond with recycle for a plant the size of Shawnee is shown below.

Materials

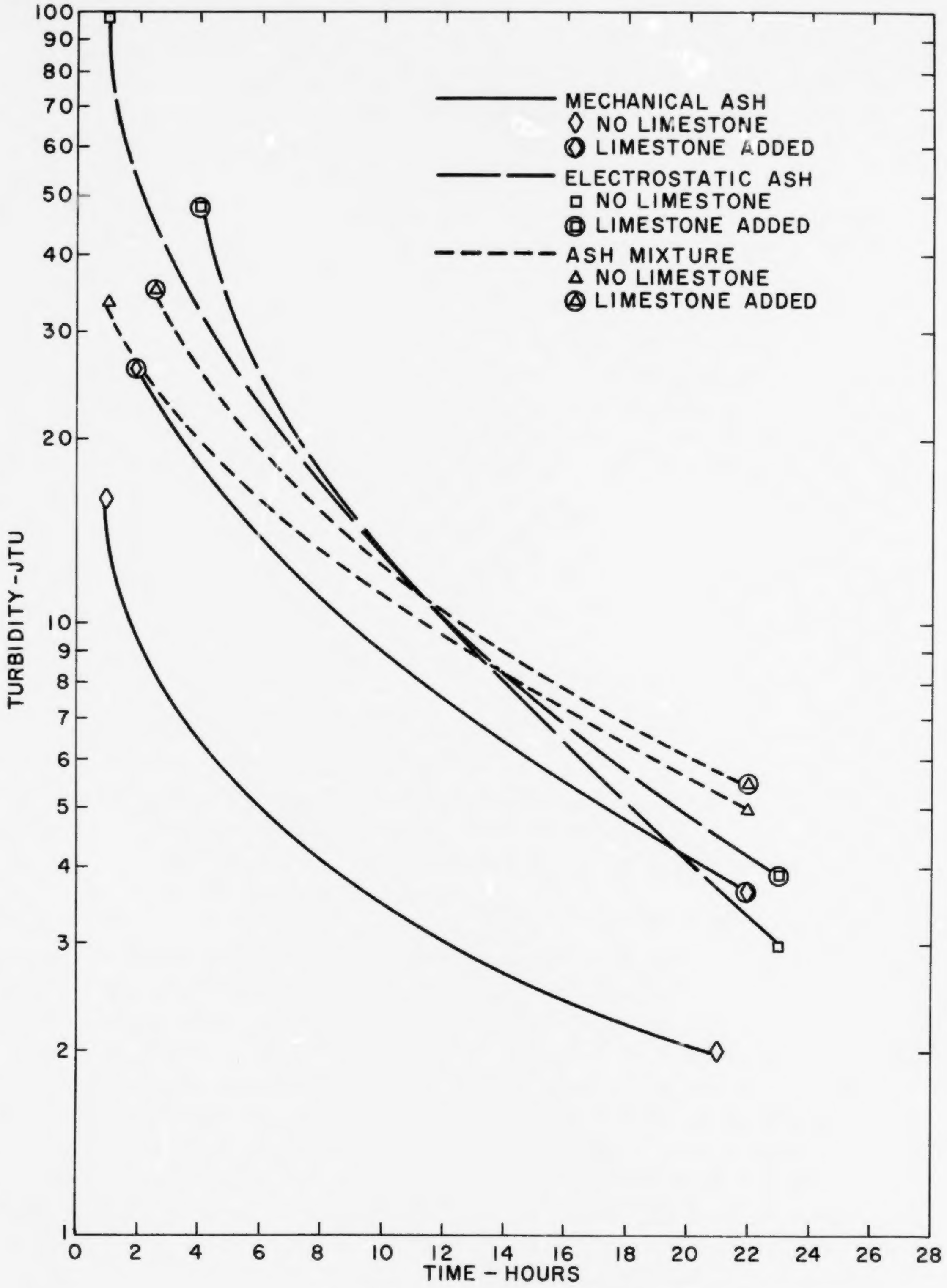
Pumping and Piping	$ 700,000
Electrical, Instruments, Controls, Miscellaneous	300,000
Installation and Construction	3,500,000
Total	$4,500,000

This cost estimate includes construction of increased pond capacity for approximately 10 years storage. The additional costs were estimated for an existing plant only; new plant costs would likely be quite different.

Limestone Effects on Settling Rates

Figure 10 shows the effect of limestone injection on ash settling rates. Slurries of ash sluice water were thoroughly mixed for five minutes and then allowed to settle for specified periods and a sample of the supernatant liquid removed for analysis. The supernatant was analyzed for turbidity by Helliqe Turbidimeter. The test conditions following limestone injection were: mechanical hopper 4.9 percent SO_4; 32.5 percent CaO, and electrostatic precipitator hopper; 6.7 percent SO_4; 24.2 percent CaO. From the figure it can be seen that limestone injection significantly increases the settling time for the mechanical sluice; however, the increase in settling time for the electrostatic sluice and mixed sluice is relatively minor. If a JTU level of 10 units is assumed to be an acceptable discharge level, increased settling time required with limestone injection is two hours. The increase in settling time requires an increase in the effective retention volume of pond for satisfactory clarification of the waste water. (The generally accepted maximum for drinking water is five JTU.) A level of 25 units would usually be considered satisfactory; and at this level, an even lower increase in settling time is required.

Figure 10



SETTLING TIMES-FLY ASH
EFFECT OF LIMESTONE ADDITION

The compaction or density of the settled ash-limestone mixture was lessened due to the increase in total amount of fine material. Analysis of the settled mixture showed the percent moisture ranged from 12 percent in the heavy ash to 52 percent in the fine material. This is essentially the same as in the fly ash alone, 9 percent to 55 percent. The density of the small sample of settled ash-limestone was 83 pounds per cubic foot while the ash alone was 94 pounds per cubic foot. An average ash density of 100 pounds per cubic foot is usually used for design purposes.

Summary and Conclusions

Since the program for the assessment of waste disposal problems associated with limestone injection was not designed as a controlled test but as an evaluation of general effects, the wide variation in water quality data was not unexpected. The resulting data is sufficient, however, to make certain conclusions concerning potential problems.

It is evident that discharge of aqueous waste from limestone injection systems can increase the dissolved solids and hardness of receiving streams sufficiently to exceed some existing stream standards, especially where plants are located contiguous to streams with relatively low critical minimum flows. In addition, sulfates and magnesium may also be above desirable concentrations, especially if a high magnesium or dolometic limestone is used. In general, if the ratio of the critical minimum flow, in cfs, to the plant capacity, in megawatts, is less than two, stream standards may be exceeded. The pH of settling pond discharges from limestone injection processes may also cause stream levels to exceed standards.

The need to provide adequate insurance for protection of the aquatic environment and beneficial water uses has led to the establishment of effluent standards. The discussion in the preceeding section of this appendix outlines several potentially toxic constituents which are likely to exceed the recommended limits of effluent standards. In addition, if a limit on the discharge of sulfates is recommended, then the process may cause sluice water concentrations to exceed the maximum value.

The normal ash sluice at Shawnee is quite alkaline, and the added unreacted calcium and injection reaction products not only raise the pH but also highly buffer the effluent in the range above 10 units. The normal ash sluice does not meet proposed standards; however, the effect of the buffering is to require such large quantities of acid for deneutralization that treatment costs become prohibitive. For a plant with a neutral pH of the normal ash sluice, the addition of limestone injection would likely cause the discharge to exceed effluent limits.

No economically feasible method for treating the dissolved solids and hardness in such a large flow is known and treatment of the highly buffered pH is also considered impractical. For example, one treatment method considered technically feasible for treatment of the dissolved solids, distillation, would require an annualized expenditure of 4 to 6 million dollars for capitalization and operation of the system for the 10-unit Shawnee plant utilizing a limestone injection process. Closed cycle sluice water operation is feasible although there will be added costs due to additional and larger pumps, larger and longer pipelines, and more frequent replacement and it is very likely that recycle of such high concentrations of dissolved solids will greatly increase maintenance problems. The increase in alkalinity and dissolved solids from closed-loop operation is quite significant even without limestone injection. Table 13 shows the water quality of a plant operating with closed cycle and no limestone.

The limestone injection process will add considerable quantities of liquid and solid wastes to normal plant operations. Theoretical determinations are generally satisfactory for estimating these quantities. The density of the settled solid waste is adversely affected, as is the particulate settling rates, although neither effect is highly significant.

Data Projection

The data presented in this appendix may be used to obtain a general estimate of the magnitude of waste disposal problems resulting from limestone injection. However, certain precautions must be taken in projecting these data to potential uses of the system. Utilization of other limestone in different modes of operation may create greater or lesser problems and the quality of the waste and its potential for water quality degradation is dependent on the type of coal, limestone feedrate or stoichiometry, type of boiler, type of ash collection system, and SO_2 removal efficiency. Table 14 shows the differences in normal sluice water quality of several plants. Additionally, the data obtained during the test phases fluctuated widely due partially to the complex chemical nature of the sluice water but apparently due more significantly to the normal variation in input parameters that occurred even during controlled test conditions. Potential users then must make an attempt to define the magnitude of the major and trace soluble constituents of their proposed system, determine the acceptability of discharge of this waste, both from the standpoint of existing and proposed standards and damage to the environment, and evaluate the costs of corrective measures.

The acceptability of such discharges has been generally based on stream standards which allow utilization of residual dilution capacity in receiving streams. However, it seems quite apparent that effluent standards will be widely implemented in the near future and that curtailment of all discharges, where feasible, is the ultimate goal. These circumstances would seem to require an evaluation of closed-cycle operation as a part of any proposed dry limestone injection system.

TABLE 13

CLOSED LOOP SYSTEM
ASH SLUICE WATER

		Alkalinity as $CaCO_3$				
Date	pH	OH	Total	SO_4	Hardness	Micromhos
February 24	12.68	1,350	1,500	250	1,607	7,270
March 22	12.20	950	1,050	225	1,231	4,900
April 12	12.40	1,200	1,400	300	1,385	6,050
April 20	12.30	950	1,050	180	1,231	4,850
April 25	12.25	1,100	1,200	200	1,231	5,400
May 4	12.20	700	800	150	906	3,610
May 16	12.15	650	800	250	923	3,855
June 30	12.10	900	1,000	200	1,009	4,200
July 18	12.40	1,400	1,500	250	1,300	4,730
July 25	12.20	1,000	1,400	200	1,370	4,825
August 5	12.20	1,000	1,100	200	1,300	4,770
August 10	12.20	1,400	1,500	200	1,368	5,560
September 9	12.20	1,200	1,300	250	1,505	5,800
September 20	12.20	1,200	1,400		1,150	5,150
October 13	12.00	600	700	250	701	3,000
November 4	12.40	1,100	1,200	250	1,334	5,520
November 17	12.30	1,400	1,500	200	1,830	6,500
November 23	12.20	700	770	180	1,419	4,830
December 7	12.40	1,100	1,200		1,112	4,300
December 14	12.20	1,100	1,200	200	1,197	4,450
January 17	12.40	1,200	1,300	250	1,710	5,420
January 30	12.30	1,200	1,300	250	1,283	4,900
February 16	12.50	1,700	2,200	300	2,052	7,550
Average	12.28	1,191	1,233	225	1,314	5,106

NOTE: Coal - 0.6 sulfur; 16 percent ash; 12,000 Btu per pound
Collection System - Mechanical, 85% efficiency

Table 14

Results of Analysis of Ash Pond Effluent From Typical Plants

Constituents (mg/l except as noted)	Plant A	Plant B	Plant C	Plant D	Plant E
Average flow (mgd)	7.0	5.0	10.0	19.0	12.0
Dissolved oxygen	9.33	9.98	8.4	9.0	8.6
pH	11.8	12.0	9.6	11.0	9.0
Alkalinity (pheno)	259	186	14.0	-	5.0
Alkalinity (total)	279	204	40.0	163	74.0
Solids (total)	464	388	422	786	237
Hardness ($CaCO_3$)	296	276	183	338	128
Calcium	114	106	65.3	130	43.6
Magnesium	3.0	3.0	5.0	3.17	4.63
Iron (ferrous)	0.0	0.01	0.0	0.02	0.0
Iron (total)	0.21	0.10	1.12	0.50	0.55
Manganese (total)	0.08	0.03	0.17	0.03	0.02
Silica	6.9	13.7	4.94	51.9	1.91
Chloride	21.9	5.69	70.4	71.6	20.6
Sulfate	84.5	69.5	93.5	145	6.7
Specific conductance (umhos)	1260	1110	551	870	332

Data Storage Format

The following pages are examples of the computer printouts of stored data. All collected water quality data is available in this retrieval format.

ELECTROSTATIC PRECIPITATOR ACTUAL TEST

ELECTROSTATIC PREC ACTU TEST LOCATION CODE SERIAL 000005

DATE	TIME	VSAMPLOC DEPTH FEET	UNIT OR RUN	TEST NO.	LIMESTONE TYPE BCR NO.	AVERAGE STOICHIO	SO2FLYAS BOILOUTL % BY WT.	SO2 IN BOT ASH % BY WT.	BEFORE CAO INJ PPM	DURING CAO INJ PPM	AFTER CAO INJ PPM	CAOFLYASH BOIL OUTL % BY WT.	LIMESTON FEEDRATE LB/LB COAL
051170	1405		10		2061	1.58			2000	1800	2000		.15
051270	1230		10		2061	1.68	4.56	5.00	1800	1640	1700	34.62	.14
051970	1250		10		2061								
052170	1055		10		2061	3.91	4.21	.50	1190	950	1190	37.90	.18
052570	1115		10		2061	4.02	3.11	.50	1200	1000	1200	40.21	.17
052770	1240		10		2061	2.18	2.68	.50	1540	1260	1460	36.70	.13
052870	1445		10		2061	1.87	2.91	.50	2080	1420	1800	43.66	.15
060170	1225		10										
060270	1645		10		2061	2.43	3.26	.50	2080	1590	1840	43.94	.17
091070	1445		10		2061	1.03	4.40	.50	1570	1290	1610	34.23	.07
091170	1240		10		2061	1.88	3.11	.24	1700	1320	1570	36.59	.10
121070	1830		10		2061	1.43	5.00	5.00	1370	2000	3030	43.70	.14
121070	1840		10		2061	1.43	5.00	5.00	1370	2000	3030	43.70	.14
121570	1220		10		2061	1.88	5.00	5.00	1870	1880	2180	44.94	.15
121670	1315		10		2061	1.88	5.00	5.00	2250	1640	1460	41.13	.15
RANGE						2.99	2.32	4.76	1060	1050	1840	10.71	.10
MEDIAN			10		2061	1.88	4.30	.50	1700	1590	1700	40.67	.15
ARITH MEAN			10		2061	2.09	4.02	2.35	1693	1522	1851	40.11	.14

ELECTROSTATIC PREC PREC TEST LOCATION CODE SERIAL 000010

DATE	TIME	VSAMPLOC DEPTH FEET	UNIT OR RUN	TEST NO.	LIMESTONE TYPE BCR NO.	AVERAGE STOICHIO	SO2FLYAS BOILOUTL % BY WT.	SO2 IN BOT ASH % BY WT.	BEFORE CAO INJ PPM	DURING CAO INJ PPM	AFTER CAO INJ PPM	CAOFLYASH BOIL OUTL % BY WT.	LIMESTON FEEDRATE LB/LB COAL
061070	1410				2061	1.72	3.76	.50	1660	1600	1700	42.21	.13
061570	1420				2061	1.72	4.17	.50	1720	1560	1800	40.77	.13
061770	1430				2061	1.63	3.99	.50	2100	1880	1950	31.92	.11
061870	1325				2061	1.65	3.05	.50	2280	2000	2100	28.72	.12
062270	1415				2061	1.65	3.12	.50	2240	2140	2300	37.01	.12
062370	1605				2061				2600	2420	2340	40.41	.14
RANGE						.09	1.12		940	860	640	13.49	.03
MEDIAN					2061	1.65	3.76	.50	2170	1940	2025	38.71	.12
ARITH MEAN					2061	1.67	3.61	.50	2100	1933	2031	36.84	.12

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ELECTROSTATIC PRECIPITATOR ACTUAL TEST

ELECTROSTATIC PREC ACTU TEST   LOCATION CODE SERIAL 000005

DATE	TIME	VSAMPLOC DEPTH FEET	COMPOSITE CODE	STREAM FLOW CUFT/SEC	PH SU	PHEN ALK CACO3 MG/L	T ALK CACO3 MG/L	RESIDUE TOTAL MG/L	RESIDUE TOT FLT MG/L	ORTHOPO4 PO4 MG/L	TOT HARD CACO3 MG/L	CALCIUM CA MG/L	MGNSIUM MG MG/L
051170	1405				11.8	520	580	14000	2200		740	330.0	410.0
051270	1230				11.9	1300	1500	26000	4900		1600	540.0	1100.0
051970	1250				12.5	2100	2200	36000	8800		3000	2600.0	400.0
052170	1055				12.8	2400	2900	48000	13000		3000	1200.0	1800.0
052570	1115				12.6	2700	2900	64000	18000		3200	320.0	2900.0
052770	1240				11.8	2300	2500	40000	10000		3000	1200.0	1800.0
052870	1445				12.2	2000	2200	33000	13000		3200	900.0	2300.0
060170	1225				11.7	800	900	19000	4000		1200	900.0	300.0
060270	1645				12.2	1800	2000	20000	7600		2300	400.0	1900.0
091070	1445				12.5	2900	3000	38500	14800		1100	900.0	200.0
091170	1240				12.3	1670	1700	39000	7000		900	700.0	200.0
121070	1830				12.5	3300	3400	39000	18000		3000	2000.0	1000.0
121070	1840				12.4	3200	3400	28000	14000		3000	2000.0	1000.0
121570	1220				12.5	3300	3400	56000	24000		3400	1700.0	1700.0
121670	1315				12.5	2400	2500	28000	12000		2800	2000.0	800.0
RANGE					1.1	2780	2820	50000	21800		2660	2280.0	2700.0
MEDIAN					12.4	2300	2500	36000	12000		3000	900.0	1000.0
ARITH MEAN					12.2	2179	2338	35233	11460		2362	1179.3	1187.3

ELECTROSTATIC PREC PREC TEST   LOCATION CODE SERIAL 000010

DATE	TIME	VSAMPLOC DEPTH FEET	COMPOSITE CODE	STREAM FLOW CUFT/SEC	PH SU	PHEN ALK CACO3 MG/L	T ALK CACO3 MG/L	RESIDUE TOTAL MG/L	RESIDUE TOT FLT MG/L	ORTHOPO4 PO4 MG/L	TOT HARD CACO3 MG/L	CALCIUM CA MG/L	MGNSIUM MG MG/L
061070	1410				10.7	170	220	19000	900		600	600.0	.0
061570	1420				10.8	240	370	20000	1200		700	600.0	100.0
061770	1430				12.0	1900	2000	19000	9600		1600	700.0	900.0
061870	1325				11.9	1500	1700	21000	4600		1260	1100.0	160.0
062270	1415				11.2	240	330	32000	1300		800	800.0	.0
062370	1605				12.0	1200	1400	25000	4500		1600	1400.0	200.0
RANGE					1.3	1730	1780	13000	8700		1000	800.0	900.0
MEDIAN					11.5	720	885	20500	2900		1030	750.0	130.0
ARITH MEAN					11.4	875	1003	22666	3683		1093	866.6	226.6

ELECTROSTATIC PRECIPITATOR ACTUAL TEST

ELECTROSTATIC PREC ACTU TEST LOCATION CODE SERIAL 000005

DATE	TIME	VSAMPLOC DEPTH FEET	CHLORIDE CL MG/L	CNDUCTVY AT25C MICROMHO	SILICA SIO2 MG/L	SODIUM NA MG/L	PTSSIUM K MG/L	MANGNESE MN UG/L	IRON TOTAL UG/L	IRON FERROUS UG/L	COPPER CU UG/L	ZINC ZN UG/L	SILVER AG UG/L	BARIUM BA UG/L
051170	1405		12	2700	4.6			80	10000					
051270	1230		8	5400	2.9			80	13000					
051970	1250		100	11000	6.2			80	9500					
052170	1055		160	16000										
052570	1115		73	23000	1.0									
052770	1240		93	13000										
052870	1445		99	16000										
060170	1225		22	5600	4.1									
060270	1645		43	9200	2.2									
091070	1445		89	19200	2.0	34.00	37.00	20	50 <					
091170	1240		71	10000	1.7	33.00	20.00	20	50 <					
121070	1830		43	23000	2.0	44.00	200.00	360	5500			380		
121070	1840		37	16000	2.0	62.00	84.00	120	1500			90		
121570	1220		57	26000	2.9	110.00	190.00	30	6500			770		
121670	1315		47	15000	1.7	60.00	49.00	40	4100			2100		
RANGE			152	23300	5.2	77.00	180.00	340	12950			2010		
MEDIAN			57	15000	2.1	52.00	66.50	80	5500			575		
ARITH MEAN			63	14073	2.7	57.16	96.66	97	5577			835		

ELECTROSTATIC PREC PREC TEST LOCATION CODE SERIAL 000010

DATE	TIME	VSAMPLOC DEPTH FEET	CHLORIDE CL MG/L	CNDUCTVY AT25C MICROMHO	SILICA SIO2 MG/L	SODIUM NA MG/L	PTSSIUM K MG/L	MANGNESE MN UG/L	IRON TOTAL UG/L	IRON FERROUS UG/L	COPPER CU UG/L	ZINC ZN UG/L	SILVER AG UG/L	BARIUM BA UG/L
061070	1410		21	1400										
061570	1420		25	1600	12.0									
061770	1430		5	14000										
061870	1325		14	5800										
062270	1415		13	1600	6.0									
062370	1605		16	5800	2.2									
RANGE			20	12600	9.8									
MEDIAN			15	3700	6.0									
ARITH MEAN			15	5033	6.7									

ELECTROSTATIC PRECIPITATOR ACTUAL TEST

ELECTROSTATIC PREC PREC TEST LOCATION CODE SERIAL 000010

DATE	TIME	VSAMPLOC DEPTH FEET	NICKEL NI UG/L	REDOX ORP MV	FLUORIDE F MG/L	COLOR PT-CO UNITS	CHROMIUM CR UG/L	TURB JKSN JU	SULFATE SO4 MG/L	SULFITE SO3 MG/L	SULFIDE S MG/L	MERCURY HG UG/L	IODIDE I MG/L	BOD 28 DAY MG/L
061070	1410					10		100	400	4.00				
061370	1420					10		150	480	3.00				
061770	1430					5		60	200	7.00				
061870	1525					5 <		100	530	6.00				
062270	1415					10		100	610	2.00				
062370	1605					5		100	500	1.00				
RANGE						5		90	410	6.00				
MEDIAN						7		100	490	3.50				
ARITH MEAN						7		101	453	3.83				

ELECTROSTATIC PREC ACTU TEST LOCATION CODE SERIAL 000005

DATE	TIME	VSAMPLOC DEPTH FEET	NICKEL NI UG/L	REDOX ORP MV	FLUORIDE F MG/L	COLOR PT-CO UNITS	CHROMIUM CR UG/L	TURB JKSN JU	SULFATE SO4 MG/L	SULFITE SO3 MG/L	SULFIDE S MG/L	MERCURY HG UG/L	IODIDE I MG/L	BOD 28 DAY MG/L
051170	1405					5 <		100	270	2.80				
051270	1230					5 <		100	360	5.00				
051970	1250					5		100	410	21.00				
052170	1055					5 <		100	620	36.00				
052570	1115					5 <		100	860	17.00				
052770	1240					5 <		75	380	22.00				
052870	1445					5 <		90	390	25.00				
060170	1225					5		100	400	7.00				
060270	1645					5 <		100	380	15.00				
091070	1445					5		100	500	11.00				
091170	1240					5		100	540	12.00				
121070	1030					10		200	750	16.00				
121070	1340					10		200	350	15.00				
121570	1220					5		125	550	20.00				
121670	1315					5		150	320	12.00				
RANGE						5		125	590	33.20				
MEDIAN						5		100	400	15.00				
ARITH MEAN						5		116	472	15.78				

ELECTROSTATIC PRECIPITATOR ACTUAL TEST

ELECTROSTATIC PREC ACTU TEST LOCATION CODE SERIAL 000005

DATE	TIME	VSAMPLOC DEPTH FEET	ALUMINUM AL UG/L	TITANIUM TI UG/L
051170	1400			
051270	1230			
051970	1250			
052170	1050			
052570	[illegible]			
052770	1200			
052970	1445			
060170	1215			
060270	1515			
091070	1445			
091170	1240			
121070	1330		4800	1 <
121070	[illegible]		6000	1 <
121570	1240		5600	1 <
121570	[illegible]		3600	1 <
RANGE			2400	
MEDIAN			5200	1
ARITH MEAN			5000	1

ELECTROSTATIC PRECIPITATOR BASE TEST

ELECTROSTATIC PREC BASE TEST

LOCATION CODE SERIAL 000001

DATE	TIME	VSAMPLOC DEPTH FEET	COMPOSITE CODE	STREAM FLOW CUFT/SEC	PH SU	PHEN ALK CACO3 MG/L	T ALK CACO3 MG/L	RESIDUE TOTAL MG/L	RESIDUE TOT FLT MG/L	ORTHOPO4 PO4 MG/L	TOT HARD CACO3 MG/L	CALCIUM CA MG/L	MGNSIUM MG MG/L
042170	1345				11.2	150	200	3000	550		250	220.0	30.0
042270	0935				7.0	0	44	770	160		120	70.0	50.0
042370	1013				8.9	12	100	2400	250		180	160.0	20.0
042370	1019				7.0	0	57	740	150		120	58.0	62.0
042470	1010				7.2	0	56	1300	160		140	60.0	80.0
042470	1020				11.1	220	280	44000	1400		840	740.0	100.0
042770	1405				11.2	190	240	24000	900		170	88.0	82.0
042770	1425				9.9	56	100	11000	350		240	220.0	20.0
042870	0725				9.8	54	110	18000	500		380	180.0	200.0
042870	0735				10.0	62	110	16000	500		380	170.0	210.0
042970	0900				7.5	0	62	1100	170		400	160.0	240.0
043070	0715				10.8	130	190	26000	800		520	290.0	230.0
050170	1245				9.8	61	94	20000	600		400	350.0	50.0
050470	0950				11.5	240	270	8300	800		240	72.0	170.0
050670	1435				11.3	220	290	19000	1200		780	720.0	60.0
051870	0905				8.2	0	79	3100	190		200	160.0	40.0
051870	0910				10.8	120	170	29000	700		480	240.0	240.0
060370	1357				11.1	120	140	4400	600		280	200.0	80.0
060470	1215				10.4	62	120	12000	440		240	160.0	80.0
060470	1220				9.5	50	140	12000	600		320	200.0	120.0
060570	1210				9.9	60	130	24000	480		240	160.0	80.0
061270	1210				8.6	12	100	5000	330		200	160.0	40.0
061270	1215				9.3	34	83	16000	500		240	180.0	60.0
061570	1105				10.5	130	170	23000	600		280	240.0	40.0
061570	1115				10.4	100	160	19000	600		320	200.0	120.0
061670	1300				10.9	250	300	16000	1000		400	320.0	80.0
061670	1315				11.0	290	340	19000	1100		400	320.0	80.0
061970	1120				10.8	120	160	18000	600		360	280.0	80.0
061970	1130				10.8	120	160	18000	600		320	280.0	40.0
062470	1000				11.1	200	260	26000	1000		560	180.0	380.0
062470	1005				11.0	200	260	23000	1000		560	240.0	320.0
120170	1035				10.0	89	170	1700	900		140	140.0	.5<
120170	1115				9.9	63	130	12000	420		170	160.0	10.0
120470	0705				9.2	22	88	3600	290		140	140.0	.5<
120470	0715				9.0	19	79	3200	290		130	110.0	20.0
120470	1035				10.0	73	130	16000	600		130	110.0	20.0
120470	1045				10.2	66	120	11000	460		110	90.0	20.0
120970	0730				11.9	570	610	28000	2100		130	110.0	20.0
120970	0740				10.9	86	98	4200	500		280	160.0	120.0
120970	1430				8.9	15	70	14000	500		440	120.0	320.0
121070	0735				10.1	65	120	16000	500		360	140.0	220.0
121470	0715				7.3	0	34	11000	260		180	140.0	40.0
030271	0955				10.7	82	120	21300	320		560		
RANGE					4.9	570	576	43260	1950		730	682.0	379.5
MEDIAN					10.1	66	130	16000	500		280	160.0	80.0
ARITH MEAN					9.9	102	156	14072	603		310	202.3	101.7

ELECTROSTATIC PRECIPITATOR BASE TEST

ELECTROSTATIC PREC BASE TEST   LOCATION CODE SERIAL 000001

DATE	TIME	VSAMPLCC DEPTH FEET	CHLORIDE CL MG/L	CNDUCTVY AT25C MICROMHO	SILICA SIO2 MG/L	SODIUM NA MG/L	PTSSIUM K MG/L	MANGNESE MN UG/L	IRON TOTAL UG/L	IRON FERROUS UG/L	COPPER CU UG/L	ZINC ZN UG/L	SILVER AG UG/L	BARIUM BA UG/L
042170	1345		12	780	11.0			580	35000					
042270	0935		9	220	9.1			380	15000					
042370	1013		7	340										
042370	1019		8	220										
042470	1010		6	240										
042470	1020		11	1600										
042770	1405		4	1400	9.1			140	17000					
042770	1425		8	530										
042870	0725		7	720	7.3			10		310				
042870	0735		7	730										
042970	0900		6	260										
043070	0715		8	1200										
050170	1245		8	850										
050470	0950		7	1200	8.8			70	4500					
050670	1435		10	1500										
051870	0905		7	270										
051870	0910		8	1000	4.9			100	16000					
060370	1357		12	930										
060470	1215		12	660										
060470	1220		13	900										
060570	1210		13	720										
061270	1210		14	470										
061270	1215		14	790										
061570	1105		11	930	7.5									
061570	1115		12	900	7.9									
061670	1300		11	1500										
061670	1315		11	1500										
061970	1120		10	940										
061970	1130		10	970										
062470	1000		7	1400										
062470	1005		7	1400										
120170	1035		1 <	1200	4.8	70.00	36.00	3100	47000			7500		
120170	1115		10	580	7.5	20.00	16.00	1500	100000			5800		
120470	0705		8	400	7.7	16.00	9.00	900	56000			2100		
120470	0715		7	400	5.2	16.00	11.00	920	55000			2000		
120470	1035		22	600	3.6	56.00	24.00	1900	90000			4200		
120470	1045		20	600	4.0	34.00	17.00	1400	110000			2600		
120970	0730		20	2500	6.7	38.00	31.00	4600	12000			140		
120970	0740		19	700	9.4	15.00	4.90	2100	28000			140		
120970	1430		21	700										
121070	0735		21	620										
121470	0715		15	340	7.6	17.00	9.00	650	87000			670		
030271	0935		7	400										
RANGE			21	2280	7.4	61.00	31.10	4590	105500			7360		
MEDIAN			10	780	7.5	20.00	16.00	900	41000	310		2100		
ARITH MEAN			10	844	7.2	32.00	17.54	1223	48035	310		2572		

ELECTROSTATIC PRECIPITATOR BASE TEST

ELECTROSTATIC PREC BASE TEST LOCATION CODE SERIAL 000001

DATE	TIME	VSAMPLOC DEPTH FEET	NICKEL NI UG/L	REDOX ORP MV	FLUORIDE F MG/L	COLOR PT-CO UNITS	CHROMIUM CR UG/L	TURB JKSN JU	SULFATE SO4 MG/L	SULFITE SO3 MG/L	SULFIDE S MG/L	MERCURY HG UG/L	IODIDE I MG/L	BOD 28 DAY MG/L
042170	1345					5		175	72	1.50				
042270	0955					10		100	31	2.00				
042370	1013					5		50	78	.20				
042370	1019					10		125	37	2.20				
042470	1010					15		200	57	.80				
042470	1020					10		100	660	.20				
042770	1405					5		65	260	.50				
042770	1425					5		90	130	.50				
042870	0725					5		100	270	.20				
042870	0735					5		100	270	.50				
042970	0900					10		175	50	1.00				
043070	0715					10		70	430	.20				
050170	1245					10		100	380	.80				
050470	0950					5 <		95	60	.50				
050670	1435					5		100	340	1.80				
051870	0905					5		150	200	1.00				
051870	0910					5		90	400	1.00				
060370	1357					5 <		40	52	4.00				
060470	1215					5		30	190	3.00				
060470	1220					5		40	350	.10<				
060570	1210					5		100	140	1.00				
061270	1210					5		150	190	5.00				
061270	1215					5		125	320	5.00				
061570	1105					5		100	260	4.00				
061570	1115					5		100	330	5.00				
061670	1300					5		150	280	2.00				
061670	1315					5		150	280	3.00				
061970	1120					5		125	300	1.00				
061970	1130					5		100	350	2.00				
062470	1000					10		100	570	2.00				
062470	1005					10		125	530	2.00				
120170	1035					5 <		100	800	7.00				
120170	1115					5 <		150	150	6.00				
120470	0705					5 <		40	100	3.00				
120470	0715					5 <		50	100	3.00				
120470	1035					5		140	360	3.00				
120470	1045					5		150	190	3.00				
120970	0730					5		65	230	4.00				
120970	0740					5		65	76	5.00				
120970	1450					5		100	360	3.00				
121070	0735					5		100	220	1.00				
121470	0745					5		175	110	3.00				
030271	0955					5		110	76	4.00				
RANGE						10		170	769	6.90				
MEDIAN						5		100	230	2.00				
ARITH MEAN						6		106	247	2.30				

```
ELECTROSTATIC PREC BASE TEST                    LOCATION CODE SERIAL 000001

  DATE   TIME VSAMPLOC ALUMINUM TITANIUM
                DEPTH      AL        TI
                 FEET     UG/L      UG/L

042170 1345
042270 0935
042370 1013
042370 1019
042470 1010
042470 1020
042770 1405
042770 1425
042870 0725
042870 0735
042970 0900
043070 0715
050170 1245
050470 0950
050670 1435
051870 0905
051870 0910
060370 1357
060470 1215
060470 1220
060570 1210
061270 1210
061270 1215
061570 1105
061570 1115
061670 1300
061670 1315
061970 1120
061970 1130
062470 1000
062470 1005
120170 1035                2800         1 <
120170 1115                2000         1 <
120470 0705                 500         1 <
120470 0715                 800         4
120470 1035                2900         1 <
120470 1045                2700         1 <
120970 0730                 200         1 <
120970 0740                 600         1 <
120970 1430
121070 0735
121470 0715                 200         1 <
030271 0955

 RANGE                     2700         3
 MEDIAN                     800         1
 ARITH MEAN                1411         1
```

ELECTROSTATIC, MICHIGAN MARL, ACTUAL TEST

ELECTRO MICH MARL ACTU TEST LOCATION CODE SERIAL 000015

DATE	TIME	VSAMPLOC DEPTH FEET	UNIT OR RUN	TEST NO.	LIMESTONE TYPE BCR NO.	AVERAGE STOICHIO	SO2FLYAS BOILOUTL % BY WT.	SO2 IN BOT ASH % BY WT.	BEFORE CAO INJ PPM	DURING CAO INJ PPM	AFTER CAO INJ PPM	CAOFLYASH BOIL OUTL % BY WT.	LIMESTON FEEDRATE LB/LB COAL
052071	1045		10		2129	2.78	3.75	.40	1330	980	1250	28.59	
052071	1440		10		2129	.96	2.68	.40	2690	2450	2680	23.12	
052171	1405		10		2129	2.74	4.79	.40	2410	1740	2200	37.23	
RANGE						1.80	2.11		1360	1470	1430	14.11	
MEDIAN			10		2129	2.74	3.75	.40	2410	1740	2200	28.59	
ARITH MEAN			10		2129	2.16	3.74	.40	2143	1723	2043	29.64	

ELECTRO MICH MARL ACTU TEST LOCATION CODE SERIAL 000015

DATE	TIME	VSAMPLOC DEPTH FEET	COMPOSITE CODE	STREAM FLOW CUFT/SEC	PH SU	PHEN ALK CACO3 MG/L	T ALK CACO3 MG/L	RESIDUE TOTAL MG/L	RESIDUE TOT FLT MG/L	ORTHOPO4 PO4 MG/L	TOT HARD CACO3 MG/L	CALCIUM CA MG/L	MGNSIUM MG MG/L
052071	1045				11.7	400	460	27000	1800				
052071	1440				12.6	2600	2700	42000	12000		1800	800.0	1000.0
052171	1405				12.5	2800	2900	51000	15000		3600	3200.0	400.0
RANGE					.9	2400	2440	24000	13200		1800	2400.0	600.0
MEDIAN					12.5	2600	2700	42000	12000		2700	2000.0	700.0
ARITH MEAN					12.2	1933	2020	40000	9600		2700	2000.0	700.0

ELECTRO MICH MARL ACTU TEST LOCATION CODE SERIAL 000015

DATE	TIME	VSAMPLOC DEPTH FEET	CHLORIDE CL MG/L	CNDUCTVY AT25C MICROMHO	SILICA SIO2 MG/L	SODIUM NA MG/L	PTSSIUM K MG/L	MANGNESE MN UG/L	IRON TOTAL UG/L	IRON FERROUS UG/L	COPPER CU UG/L	ZINC ZN UG/L	SILVER AG UG/L	BARIUM BA UG/L
052071	1045		30	2200										
052071	1440		44	13600	15.0	60.00	83.00	930	3400		220	2800		
052171	1405		46	16800	18.0	56.00	91.00	110	3000		130	460		
RANGE			16	14600	3.0	4.00	8.00	820	400		90	2340		
MEDIAN			44	13600	16.5	58.00	87.00	520	3200		175	1630		
ARITH MEAN			40	10866	16.5	58.00	87.00	520	3200		175	1630		

ELECTROSTATIC, MICHIGAN MARL, ACTUAL TEST

ELECTRL MICH MARL ACTU TEST

LOCATION CODE SERIAL 000015

DATE	TIME	VSAMPLOC DEPTH FEET	NICKEL NI UG/L	REDOX OFP MV	FLUORIDE F MG/L	COLOR PT CO UNITS	CHROMIUM CR UG/L	TURB JKSN JU	SULFATE SO4 MG/L	SULFITE SO3 MG/L	SULFIDE S MG/L	MERCURY HG UG/L	IODIDE I MG/L	BOD 28 DAY MG/L
052071	1045					10		125	310	1.00				
052071	1440					10		100	460	17.00				
052171	1405					5		125	640	23.00				
RANGE						[illegible]		25	330	22.00				
MEDIAN						10		125	460	17.00				
ARITH MEAN						8		116	470	13.66				

ELECTRL MICH MARL ACTU TEST

LOCATION CODE SERIAL 000015

DATE	TIME	VSAMPLOC DEPTH FEET	ALUMINUM AL UG/L	TITANIUM TI UG/L
052071	1045			
052071	1440		7	1 <
052171	1405		6	1 <
RANGE			1	
MEDIAN			[illegible]	1
ARITH MEAN			[illegible]	1

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MECHANICAL, ARAGONITE, ACTUAL TEST

MECH. ARAGONITE ACTU TEST LOCATION CODE SERIAL 000014

DATE	TIME	VSAMPLOC DEPTH FEET	UNIT OR RUN	TEST NO.	LIMESTONE TYPE BCR NO.	AVERAGE STOICHIO	SO2FLYAS BOILOUTL % BY WT.	SO2 IN BOT ASH % BY WT.	BEFORE CAO INJ PPM	DURING CAO INJ PPM	AFTER CAO INJ PPM	CAOFLYASH BOIL OUTL % BY WT.	LIMESTON FEEDRATE LB/LB COAL
030371	1005		10		1683	3.26	2.50	.22	1540	850	1150	43.45	
030471	1040		10		1683	3.16	3.73	.22	1300	1020	1080	30.46	
030471	1205		10		1683	3.08	2.68	.20	1150	940	1110	30.15	
030471	1530		10		1683	1.67	3.16	.29	1210	990	1140	25.99	
030571	1050		10		1683	3.69	3.56	.27	1290	900	1200	39.54	
RANGE						2.02	1.23	.09	390	170	120	17.46	
MEDIAN			10		1683	3.16	3.16	.22	1290	940	1140	30.46	
ARITH MEAN			10		1683	2.97	3.12	.24	1298	940	1136	33.91	

MECH. ARAGONITE ACTU TEST LOCATION CODE SERIAL 000014

DATE	TIME	VSAMPLOC DEPTH FEET	COMPOSITE CODE	STREAM FLOW CUFT/SEC	PH SU	PHEN ALK CACO3 MG/L	T ALK CACO3 MG/L	RESIDUE TOTAL MG/L	RESIDUE TOT FLT MG/L	ORTHOPO4 PO4 MG/L	TOT HARD CACO3 MG/L	CALCIUM CA MG/L	MGNSIUM MG MG/L
030371	1005				11.7	340	380	21100	1500		1100	900.0	200.0
030471	1040				12.7	3100	3200	14900	13500		3400	3000.0	400.0
030471	1205				12.6	2500	2600	24200	10200		3600	3000.0	600.0
030471	1530				12.6	2800	2900	28600	11700		3600	3200.0	400.0
030571	1050				12.6	3000	3100	18000	12300		3400	2900.0	500.0
RANGE					1.0	2760	2820	13700	12000		2500	2300.0	400.0
MEDIAN					12.6	2800	2900	21100	11700		3400	3000.0	400.0
ARITH MEAN					12.4	2348	2436	21360	9840		3020	2600.0	420.0

MECH. ARAGONITE ACTU TEST LOCATION CODE SERIAL 000014

DATE	TIME	VSAMPLOC DEPTH FEET	CHLORIDE CL MG/L	CNDUCTVY AT25C MICROMHO	SILICA SIO2 MG/L	SODIUM NA MG/L	PTSSIUM K MG/L	MANGNESE MN UG/L	IRON TOTAL UG/L	IRON FERROUS UG/L	COPPER CU UG/L	ZINC ZN UG/L	SILVER AG UG/L	BARIUM BA UG/L
030371	1005		31	1800	24.0	36.00	19.00	920	92000			3100		
030471	1040		6	15000	.6	14.00	19.00	240	2000			100		
030471	1205		5	11400	.9	12.00	19.00	130	1000			20		
030471	1530		22	12600	.8	10.00	15.00	360	1300			80		
030571	1050		22	12900	.9	7.20	23.00	30	680			10		
RANGE			26	13200	23.4	28.80	8.00	890	91320			3090		
MEDIAN			22	12600	.9	12.00	19.00	240	1300			80		
ARITH MEAN			17	10740	5.4	15.84	19.00	336	19396			662		

MECHANICAL, ARAGONITE, ACTUAL TEST

MECH. ARAGONITE ACTU TEST LOCATION CODE SERIAL 000014

DATE	TIME	VSAMPLOC DEPTH FEET	NICKEL NI UG/L	REDOX ORP MV	FLUORIDE F MG/L	COLOR PT-CO UNITS	CHROMIUM CR UG/L	TURB JKSN JU	SULFATE SO4 MG/L	SULFITE SO3 MG/L	SULFIDE S MG/L	MERCURY HG UG/L	IODIDE I MG/L	BOD 28 DAY MG/L
030371	1005					5		175	380	11.00				
030471	1040					5		125	270	15.00				
030471	1205					5		125	220	11.00				
030471	1530					5 <		100	320	16.00				
030571	1050					10		100	170	13.00				
RANGE						5		75	210	5.00				
MEDIAN						5		125	270	13.00				
ARITH MEAN						6		125	272	13.20				

MECH. ARAGONITE ACTU TEST LOCATION CODE SERIAL 000014

DATE	TIME	VSAMPLOC DEPTH FEET	ALUMINUM AL UG/L	TITANIUM TI UG/L
030371	1005		100	
030471	1040		5600	
030471	1205		100	
030471	1530		200	
030571	1050		200	
RANGE			5500	
MEDIAN			200	
ARITH MEAN			1240	

Appendix H
Additional Heat Requirement Calculations

Determination of Additional Heat Requirement Calculations in Coal-Fired Boilers Due to Limestone Injection

Injection of dry ground limestone ($CaCO_3$) into coal-fired boilers for reaction with sulfur oxides in the flue gas consumes a portion of the heat normally used in producing power. Operating experience for an existing 150-MW plant without limestone injection shows that generation of electricity requires approximately .78 lbs. coal per kWh. However, when dry limestone injection is used, additional coal must be supplied to the boiler to compensate for the net heat change resulting from calcination of the limestone and $CaSO_4$ formation.

A schematic diagram of the boiler showing inlet and exit temperatures of reactants and products is shown in figure H-1.

The total heat effect of limestone injection is calculated in the following case examples, based on a 150-MW unit burning coal containing either 0.8%, 3% or 5% sulfur, 92% of which is emitted as SO_2 in the boiler flue gas. For the 0.8% sulfur coal, the heat effect is shown assuming injection of a 5 to 1 mole ratio of calcium carbonate to sulfur in coal, whereas for 3% and 5% sulfur coals, the heat effect is shown for injection of a 2 to 1 mole ratio of calcium carbonate to sulfur in coal. EPA-TVA test data for dry limestone injection indicated that for a 0.8% sulfur coal, 5% of the SO_2 in the gas reacts with the calcium carbonate for each unit of stoichiometry injected, whereas data for 3% and 5% sulfur coals showed that 10% of the SO_2 reacts per unit of calcium carbonate stoichiometry injected.

Although it is not certain whether the injected limestone sequentially calcines, then reacts with SO_2 as in equations (1) and (2) below or reacts directly as in equation (3), the thermodynamics of the system are the same.

$$CaCO_3 \longrightarrow CaO + CO_2 \qquad (1)$$

$$CaO + SO_2 + 1/2\ O_2 \longrightarrow CaSO_4 \qquad (2)$$

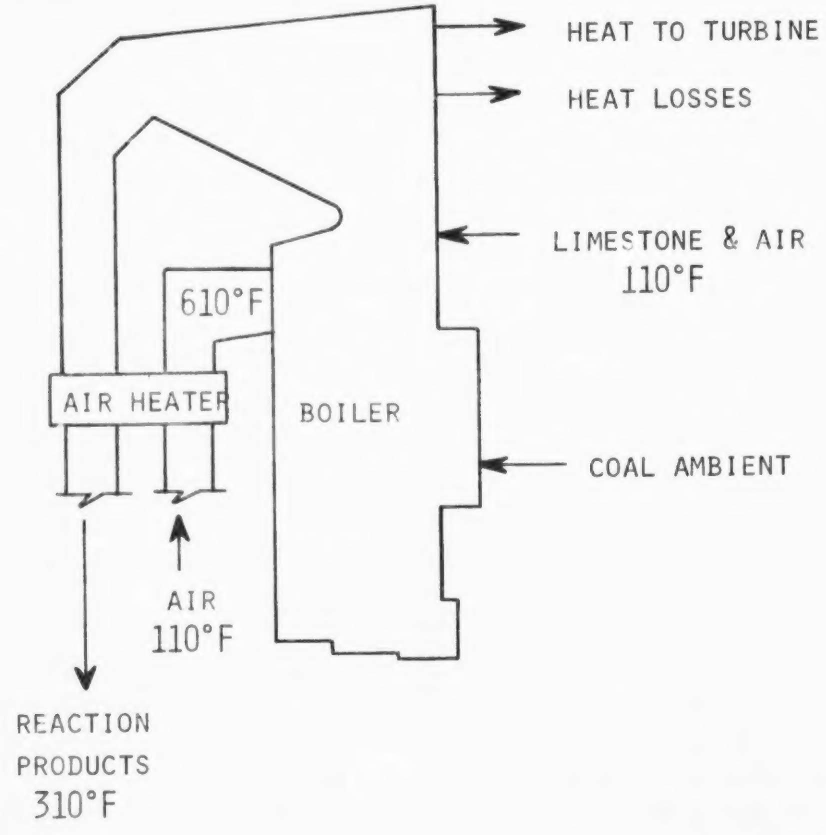
$$CaCO_3 + SO_2 + 1/2\ O_2 \longrightarrow CaSO_4 + CO_2 \qquad (3)$$

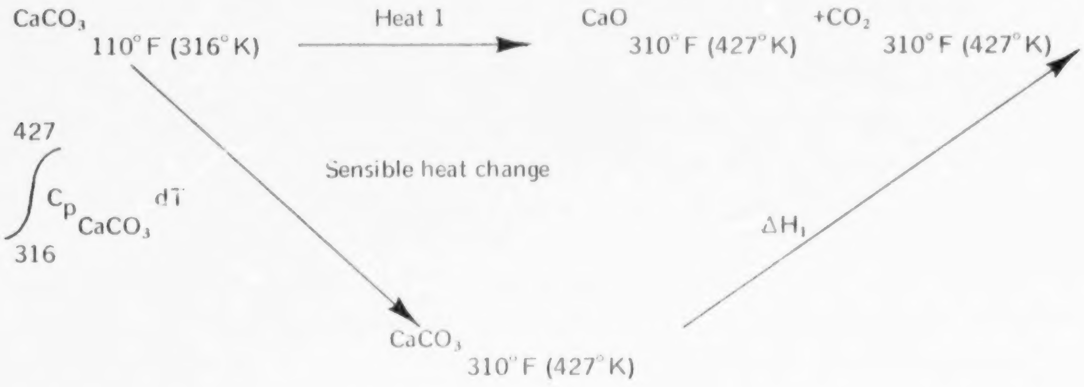
Since the total heat change involved in the reactions is a state function and hence, dependent only upon the inlet and outlet conditions of the reactants and products, the total heat effect is independent of the reaction path and intervening temperatures. So that all computations and results can be given in terms of $CaCO_3$ input to the boiler, equations (1) and (3) are used in the examples to follow. Quantity X represents the fraction of the injected limestone which reacts with SO_2 (eq. 3) and 1-X represents the fraction of limestone leaving the boiler as calcium oxide (eq. 1). All calculations are based on the calcite polymorph.

The enthalpy relation for reaction (1) is shown below.

FIGURE H-1

REACTANT AND PRODUCT TEMPERATURES FROM POWER PLANT BOILERS WITH DRY LIMESTONE INJECTION





where ΔH_1 is the heat of reaction at 310° F (427°K),

$$\int_{316}^{427} C_{p_{CaCO_3}} \, dT$$

represents the sensible heat change of $CaCO_3$ and Heat 1 is the total heat effect expressed in cal/gram-mole. Thus,

$$\text{Heat 1} = \Delta H_1 + \int_{316}^{427} C_{p_{CaCO_3}} \, dT \qquad (4)$$

This heat effect, Heat 1, is calculated as follows. The standard heat of reaction, $\Delta H_1{}^\circ$, of $CaCO_3$ to CaO and CO_2 is calculated to be 42,500 cal/gram-mole from tabulated heats of formation (1) by means of equation (5)

$$\Delta H_1{}^\circ = \Delta H^\circ_{f_{CaO}} + \Delta H^\circ_{f_{CO_2}} - \Delta H^\circ_{f_{CaCO_3}} \qquad (5)$$

where $\Delta H^\circ{}_f$ represents the standard heat of formation of the compound in question.

The heat of reaction at 310°F. (427° K.), ΔH_1, is now calculated from equation (6)

$$\Delta H_1 = \int \Delta C^1_p \, dT + \Delta H^1_0 \qquad (6)$$

where ΔC^1_p represents the difference in reactant and product heat capacities and ΔH^1_0 is an integration constant evaluated from the known standard heat of reaction, $\Delta H_1{}^\circ$. Because enthalpy is a state function, as discussed earlier, its value depends only on initial and final states and not reaction path. Although calcium carbonate is heated to 1800°F. or higher in the boiler, the heat of reaction depends only on inlet reactant and exit product temperatures indicated in figure H-1.

The necessary heat capacity data are taken from a Bureau of Mines publication (2) from which the following equation for calculating ΔC^1_p was derived.

$$\Delta C_p^1 = -2.74 - 2.06 \times 10^{-3}\, T + 2.58 \times 10^{5}\, T^{-2} \qquad (7)$$

where T = temperature, °K

Substitution of ΔC_p^1 into equation (6) followed by integration yields equation (8) which is used to calculate the heat of reaction, ΔH_1 at 310° F.

$$\Delta H_1 = -2.74\, T - 1.03 \times 10^{-3}\, T^2 - \frac{2.58 \times 10^5}{T} + 44{,}274 \qquad (8)$$

The heat of reaction was calculated to be +42,312 cal/gram-mole at 310° F (427° K).

The sensible heat portion of Heat 1 was found from equation (9) to be +2,479 cal/gram-mole.

$$(\text{Sensible Heat})\ CaCO_3 = \int_{316}^{427} C_{p_{CaCO_3}}\, dT \qquad (9)$$

Substitution of the sensible heat and heat of reaction, ΔH_1, into equation (4), yields a total calcination heat effect, Heat 1, of 44,791 cal/gram-mole.

A fraction (X) of the calcium carbonate injected reacts with sulfur dioxide and sulfur trioxide in the combustion gases, as shown in Equation (3). Usually SO_3 content of flue gas is a small fraction of the total sulfur oxides and for purposes here is assumed as SO_2. The enthalpy changes of calcium sulfate formation are shown below.

$$\begin{tikzcd}
\underset{110^\circ F(316^\circ K)}{CaCO_3} + \underset{310^\circ F(427^\circ K)}{SO_2} + \underset{310^\circ F(427^\circ K)}{1/2\, O_2} \arrow[r, "\text{Heat 2}"] \arrow[d, "\int_{316}^{427} C_{p_{CaCO_3}} dT \quad \text{Sensible Heat Change}"'] & \underset{310^\circ F(427^\circ K)}{CaSO_4} + \underset{310^\circ F(427^\circ K)}{CO_2} \\
\underset{310^\circ F(427^\circ K)}{CaCO_3} + \underset{310^\circ F(427^\circ K)}{SO_2} + \underset{310^\circ F(427^\circ K)}{1/2\, O_2} \arrow[ur, "\Delta H_2"'] &
\end{tikzcd}$$

where $\int_{316}^{427} Cp_{CaCO_3}\, dT$, and ΔH_2

are the sensible heat change of $CaCO_3$ and the heat of reaction at 310° F. There are no sensible heat changes for O_2 and SO_2 because these materials are already present in the absence of limestone injection and therefore make no additional heat demands. The total heat effect of calcium sulfate formation, Heat 2, is

$$\text{Heat } 2 = \int_{316}^{427} C_{p_{CaCO_3}}\, dT + \Delta H_2 \qquad (10)$$

As with Heat 1, this heat effect is calculated from heat capacity data and standard heats of formation. The standard heat of reaction, $\Delta H_2{}^\circ$, is calculated to be -76,970 cal/gram-mole from equation (11).

$$\Delta H_2{}^\circ = \Delta H^\circ_{f_{CO_2}} + \Delta H^\circ_{f_{CaSO_4}} - \Delta H^\circ_{f_{SO_2}} - \Delta H^\circ_{f_{CaCO_3}} \tag{11}$$

The heat of reaction, ΔH_2, at 310° F is calculated from equation (12) where ΔC_p^2 and ΔH_o^2 are respectively, the difference between product and reactant heat capacities and an integration constant evaluated from the standard heat of reaction, $\Delta H_2{}^\circ$.

$$\Delta H_2 = \int \Delta C_p{}^2 \, dT + \Delta H_o{}^2 \tag{12}$$

The following equation for calculating ΔC_p^2 was derived:

$$\Delta C_p^2 = -12.05 + 18.08 \times 10^{-3}\, T + 6.18 \times 10^5 \; T^{-2} \tag{13}$$

Substitution of $\Delta C_p{}^2$ into equation (12) followed by integration yields equation (14) from which the heat of reaction ΔH_2 at 310° F is calculated to be -78,306 cal/gram-mole.

$$\Delta H_2 = -12.05T + 9.04 \times 10^{-3} \; T^2 + \frac{6.18 \times 10^5}{T} - 76{,}256 \tag{14}$$

The sensible heat change of $CaCO_3$ is found to be 2,479 cal/gram-mole.

Substitution of this value and ΔH_2 into equation (10) yields a heat effect, Heat 2, of -75,827 cal/gram-mole.

For example, the limestone can be considered 95% $CaCO_3$. The remaining 5% is assumed to be 4.5% inert impurities with the same heat capacity as calcium carbonate and 0.5% liquid H_2O. The net heat effect, Heat 3, due to inert impurities is found from equation (15) to be +117 cal/gram-mole of $CaCO_3$ used

$$\text{Heat 3} = 0.045 \int_{316}^{427} C_{p_{CaCO_3}} \, dT \tag{15}$$

Enthalpy relations for the water injected into the boiler along with the limestone are shown below

$$H_2O \; (\ell\,,316^\circ K) \xrightarrow{h_1} H_2O\;(\ell\,,373^\circ K) \xrightarrow[h_2]{} H_2O\;(g,373^\circ K) \xrightarrow{h_3} H_2O\;(g,427^\circ K)$$

The heat effect, Heat 4, due to water injection is the sum of the individual heat effects, h_1 h_2 and h_3, shown above, and found to be 311 cal/gram-mole of $CaCO_3$.

The total heat consumed by limestone injection is found from equation (16) where N_{CaCO_3}, and X are, respectively, gram-moles of calcium carbonate, and the fractional conversion of $CaCO_3$ to $CaSO_4$.

$$\text{Total Heat} = N_{CaCO_3} \left[(1-X)(\text{Heat 1}) + X\,(\text{Heat 2}) + \text{Heat 3} + \text{Heat 4}\right] \tag{16}$$

The four terms of equation (16) represent, respectively, heat consumed in calcining calcium carbonate, conversion of calcium carbonate to calcium sulfate, sensible heat of the inert impurities in the limestone and enthalpy changes for 0.5% liquid water. Results in Table 1 show that significant heat effects are due primarily to $CaCO_3$ calcination and $CaSO_4$ formation.

A 150-MW unit (requiring .780 lbs. coal/kWh with no limestone injection) consumes 117,000 lbs. of coal/hr. For Base Case 1, this coal requires 6.63×10^4 gram-mole of $CaCO_3$/hr. which is equivalent to a heat loss of 2.62×10^9 gram cal/hr. (1.04×10^7 Btu/hr.). Assuming 12,000 Btu/lb. of coal, to maintain a 150-MW output, 868 lb/hr. of additional coal are required to make up for heat losses due to the first increment of $CaCO_3$. This additional coal will require an additional but smaller increment of $CaCO_3$ which in turn requires more coal, etc. By iteration the total additional coal required was found to be 874 lbs/hr. of coal which is equivalent to a coal firing rate of .786 lbs. coal /kWh. Similar calculations were made for Base Cases 2 and 3. Results are shown below:

	% S in Coal	Additional Coal-lb/hr.	Stoichiometry	Total Coal Requirement lbs/hr.	Total Coal Requirement lbs/kWh
Base case 1	0.8	874	5X	117,874	.786
Base case 2	3.0	1127	2X	118,127	.788
Base case 3	5.0	1901	2X	118,901	.793

Defining efficiency losses as the percentage ratio of additional coal to total coal required without injection, power plant efficiency losses due to limestone injection for the 0.8, 3.0 and 5.0 percent S cases were calculated to be 0.75%, 0.97%, and 1.62% respectively.

References

1. Handbook of Chemistry, N. A. Lange, Ed. 10th Edition, McGraw-Hill, 1967.
2. K. K. Kelley, Contributions to the Data on Theoretical Metallurgy, High-Temperature Heat - Content, Heat Capacity, and Entropy Data for the Elements and Inorganic Compounds, U.S. Bureau of Mines, Bulletin 584.